QUANTUM EFFICIENCY MEASUREMENTS

OF

a-C:H BASED PHOTOVOLTAIC CELLS

A Thesis Presented to
The Faculty of the
Fritz J. and Dolores H. Russ
College of Engineering and Technology
Ohio University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

Michael Maldei

March 1997
ACKNOWLEDGEMENTS

The experimental work for this M.S. degree was performed at two different locations. The fabrication of a-C:H based photovoltaic devices was done in the Ohio University Accelerator Laboratory, while the quantum efficiency measurements were performed at Energy Conversion Devices (ECD), Inc. in Troy, Michigan. There is a multitude of individuals at these two facilities who have lend me support or guidance during this masters project and to which I would like to express my gratitude.

I would like to acknowledge Dr. Henryk Lozykowski in the ECE Department of Ohio University for being an encouraging research advisor for this work and I would like to thank him for the extra effort he took in teaching me the fundamentals of semiconductors.

My sincere thanks go to Dr. David C. Ingram in the Physics Department of Ohio University for providing the vacuum deposition equipment and supplies in the Accelerator Laboratory. It shall also be acknowledged that Dr. Ingram provided me with substantial financial support during this research.

Further, I want to recognize Dr. Xunming Deng in the Photovoltaic Development Group at Energy Conversion Devices, Inc. for giving me the opportunity to work for ECD during summer 1996. It is especially appreciated that Dr. Deng let me do the research for this M.S. degree at ECD's quantum efficiency measurement system.

Finally, I want to thank my best friend Petra Stumm for her continued support.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1. a-C:H for photovoltaic devices</td>
<td>6</td>
</tr>
<tr>
<td>2.2. Quantum efficiency measurement</td>
<td>10</td>
</tr>
<tr>
<td>3. EXPERIMENTAL METHODS AND SETUP</td>
<td>13</td>
</tr>
<tr>
<td>3.1. Deposition system for the fabrication of a-C:H solar cells</td>
<td>13</td>
</tr>
<tr>
<td>3.2. Quantum efficiency measurement</td>
<td>15</td>
</tr>
<tr>
<td>3.2.1. Theory of quantum efficiency determination</td>
<td>15</td>
</tr>
<tr>
<td>3.2.2. Quantum efficiency measurement system</td>
<td>30</td>
</tr>
<tr>
<td>3.2.3. Software</td>
<td>33</td>
</tr>
<tr>
<td>3.2.4. Calibration procedure</td>
<td>36</td>
</tr>
<tr>
<td>3.2.5. Measurement procedure</td>
<td>39</td>
</tr>
<tr>
<td>4. RESULTS AND DISCUSSION</td>
<td>40</td>
</tr>
<tr>
<td>4.1. Characterization of a-C:H and fabricated devices</td>
<td>40</td>
</tr>
<tr>
<td>4.1.1. Absorption coefficients and bandgaps of a-C:H</td>
<td>40</td>
</tr>
<tr>
<td>4.1.2. Low resistance contacts to a-C:H and fabricated devices</td>
<td>43</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 2-1: Bandgaps of amorphous carbon reported by several researchers . . . 8

Table 4-1: Polarity of obtained photovoltages; neg. lead of voltmeter at partially transparent front contact, pos. lead at back contact . . . . . . . 45
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1-1:</td>
<td>Schematic of a semiconductor band structure</td>
<td>2</td>
</tr>
<tr>
<td>Figure 1-2:</td>
<td>Potential energy diagram of a pn homojunction solar cell</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1-3:</td>
<td>Schematic electronic density of states of amorphous carbon, from reference [4]</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2-1:</td>
<td>Influence of deposition parameters on the optical bandgap in a-C:H, replotted from: A) [2], B) [8] and C) [9]</td>
<td>7</td>
</tr>
<tr>
<td>Figure 3-1:</td>
<td>Deposition of a-C:H from electric arc</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3-2:</td>
<td>Two methods of device illumination: A) collimated light exceeding the device area; B) focused light with spot size smaller than the device area</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3-3:</td>
<td>Typical quantum efficiency curve for an amorphous, hydrogenated silicon (a-Si:H) single junction solar cell</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3-4:</td>
<td>Evaluation of data for spectral response or quantum efficiency</td>
<td>25</td>
</tr>
<tr>
<td>Figure 3-5:</td>
<td>Optical setup for quantum efficiency measurement system</td>
<td>30</td>
</tr>
<tr>
<td>Figure 3-6:</td>
<td>Electrical setup for quantum efficiency measurement system</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3-7:</td>
<td>Main menu of quantum efficiency measurement software</td>
<td>33</td>
</tr>
<tr>
<td>Figure 3-8:</td>
<td>Quantum efficiency as a function of wavelength for the crystalline silicon calibration detector</td>
<td>36</td>
</tr>
<tr>
<td>Figure 3-9:</td>
<td>Verification of system calibration by remeasuring the quantum efficiency of the calibration detector</td>
<td>38</td>
</tr>
<tr>
<td>Figure 4-1:</td>
<td>Absorption coefficients of a-C:H films deposited by electric arc evaporation</td>
<td>41</td>
</tr>
<tr>
<td>Figure 4-2:</td>
<td>Tauc-bandgaps of electric arc deposited a-C:H films</td>
<td>42</td>
</tr>
<tr>
<td>Figure 4-3:</td>
<td>Fabricated Schottky and heterojunction devices</td>
<td>44</td>
</tr>
<tr>
<td>Figure 4-4:</td>
<td>Proposed band diagram for ITO (Donnelly Corp.)/a-C:H/Au contact; a-C:H was deposited at a hydrogen pressure &lt; 0.1 mTorr</td>
<td>46</td>
</tr>
<tr>
<td>Figure 4-5:</td>
<td>Proposed band diagram for Cr/a-C:H/Au contact; a-C:H was deposited at a hydrogen pressure of 2 mTorr</td>
<td>48</td>
</tr>
<tr>
<td>Figure 4-6:</td>
<td>Proposed band diagram for Au/a-C:H/p-type c-Si heterojunction device</td>
<td>49</td>
</tr>
<tr>
<td>Figure 4-7:</td>
<td>Schematic diagram of the short-circuit current versus time for a solar cell subjected to a pulsed light source</td>
<td>51</td>
</tr>
<tr>
<td>Figure 4-8:</td>
<td>Schematic diagram of the short-circuit current versus time for a solar cell subjected to a pulsed light source at high pulse frequency</td>
<td>52</td>
</tr>
<tr>
<td>Figure 4-9:</td>
<td>Schematic showing the lock-in amplifier DC output voltage as a function of chopper frequency</td>
<td>53</td>
</tr>
<tr>
<td>Figure 4-10:</td>
<td>Schematic of system frequency response leading to false quantum efficiency measurements: A) Overestimate of QE, B) Underestimate of QE</td>
<td>54</td>
</tr>
<tr>
<td>Figure 4-11:</td>
<td>Normalized lock-in amplifier output voltage versus chopper frequency for the c-Si calibration detector at monochromatic light of 450 nm and 650 nm</td>
<td>55</td>
</tr>
<tr>
<td>Figure 4-12:</td>
<td>Normalized lock-in amplifier output voltage versus chopper frequency for the a-C:H test cell at incident monochromatic light of 370 nm</td>
<td>57</td>
</tr>
<tr>
<td>Figure 4-13:</td>
<td>Schematic showing the response of the calibration detector as a function of the incident radiant power</td>
<td>59</td>
</tr>
<tr>
<td>Figure 4-14:</td>
<td>Lock-in amplifier output voltage versus radiant power for the c-Si calibration detector</td>
<td>61</td>
</tr>
<tr>
<td>Figure 4-15:</td>
<td>Lock-in amplifier output voltage versus radiant power for the ITO/a-C:H/Au heterojunction device</td>
<td>62</td>
</tr>
<tr>
<td>Figure 4-16:</td>
<td>Quantum efficiency versus wavelength curve repeated five times for an a-Si:H single junction solar cell</td>
<td>63</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4-17</td>
<td>Quantum efficiency versus wavelength curve for an a-C:H based photovoltaic device</td>
<td>66</td>
</tr>
<tr>
<td>4-18</td>
<td>Quantum efficiency curve for an ITO/a-C:H/Au heterojunction</td>
<td>68</td>
</tr>
<tr>
<td>4-19</td>
<td>Quantum efficiency curve for a Cr/a-C:H/Au Schottky contact</td>
<td>70</td>
</tr>
<tr>
<td>4-20</td>
<td>Quantum efficiency curve for a Au/a-C:H/p-type c-Si heterojunction solar cell device</td>
<td>72</td>
</tr>
</tbody>
</table>
1. Introduction

Solar cells are solid state devices which directly convert sunlight into electrical energy. This energy conversion is achieved without emission of any air pollutants or hazardous by-products in contrast to electricity generated from nuclear or coal-fired power plants. Photovoltaic electricity generation also involves no moving parts and is therefore inherently reliable. The most attractive feature of the photovoltaic energy conversion process is that the source of energy, the sun, is free of charge. Since the discovery of the photovoltaic effect in 1839 by the French scientist Edmund Becquerel, solar cell conversion efficiencies have increased steadily. In proportion to this progress, the price of solar electricity declined to about $0.20 per KWh today. However, even more effort needs to be directed toward improving device efficiencies to make solar energy competitive to electricity generated from conventional energy sources.

Many crystalline and amorphous semiconductors have been investigated to produce efficient solar cells. Among these are crystalline silicon (c-Si), amorphous, hydrogenated silicon (a-Si:H) and germanium (a-Ge:H) as well as alloys like gallium arsenide (GaAs), cadmium telluride (CdTe) and copper indium diselenide (CuInSe₂). All these materials share an important semiconductor property which is the bandgap. According to Figure 1-1, the bandgap $E_g$ in a semiconductor is located between the top of the valence band electron energy states $E_v$ and the bottom of the conduction band electron energy states $E_c$. Therefore, the bandgap is essentially an electron energy region in which the density of electron energy states is very low. Based on the bandgap of a semiconductor, the
maximum theoretical conversion efficiency for a photovoltaic device can be calculated. This calculation will be explained with the help of Figure 1-2, in which the potential energy diagram for a pn homojunction solar cell is shown. The pn homojunction consists of two adjacent semiconductor regions of which one region is n-type doped while the other region is p-type doped. Conduction band electrons from the n-type region diffuse into the p-type region where they recombine with holes in the valence band. This movement of electrons results in a local charge disequilibrium which causes an internal electric field. If the device is illuminated, photons excite electrons in the p-type material into the conduction band. These minority carriers in the p-type region are attracted by the electric field and drift toward the n-type region where they are collected. However, sunlight consists of a photon energy distribution and not all photons contribute to the generated current. Photons of lower energy than the semiconductor bandgap cannot excite
Figure 1-2: Potential energy diagram of a pn homojunction solar cell

electrons from the valence band into the conduction band and thus are useless for electric current generation. Photons of higher energy than the bandgap contribute to the photogenerated current, but the fraction of energy that is larger than the bandgap is dissipated as thermal energy. The maximum theoretical conversion efficiency for a single junction solar cell is predicted for a bandgap of about 1.45 eV.

With respect to solar cell fabrication, carbon based semiconductor materials have received relatively little attention so far. The two well-known structural configurations of crystalline carbon are graphite and diamond. Graphite is a semimetal ($E_g = -0.04$ eV) while diamond is a wide bandgap semiconductor ($E_g = 5$ eV). Neither are useful candidates for photovoltaic energy conversion. Less well known is carbon in its amorphous structure, which is an intermediate between graphite and diamond and has a variable bandgap. Amorphous carbon is referred to as hydrogenated, amorphous carbon
(a-C:H) or just amorphous carbon (a-C). This distinction refers to whether hydrogen is present in the amorphous structure. Bandgap values in amorphous carbon have been reported in the range of 0.4-4.1 eV [1, 2, 3]. This bandgap range includes the optimum bandgap value of 1.45 eV for a single junction photovoltaic device.

Carbon atoms can form three different types of bonding configurations, which are sp³, sp² and sp¹. These configurations are caused by hybridization of different atomic orbitals. The sp³ configuration leads to the formation of a single or σ bond between carbon atoms. Carbon atoms that are sp² hybridized form a double bond with each other. This double bond consists of one σ and one π bond. Finally, the sp¹ configuration results in a triple bond between carbon atoms and consists of one σ and two π bonds. To various degrees, all of these bonding configurations are present in a-C and a-C:H. The significance of π bonds in a-C and a-C:H will be explained using Figure 1-3.

![Schematic electronic density of states of amorphous carbon](image-url)

**Figure 1-3:** Schematic electronic density of states of amorphous carbon, from reference [4]
π bonds represent electron energy states which are more weakly bound than electrons in σ states. Therefore, π states are located closer to the Fermi level than σ states and control the width of the bandgap. The presence of π bonds in a-C and a-C:H is the reason why it is possible to change the bandgap through deposition conditions. This is an advantage over amorphous, hydrogenated silicon (a-Si:H) and amorphous, hydrogenated germanium (a-Ge:H), because these materials can form only σ bonds. To significantly change the bandgap in a-Si:H and a-Ge:H, these materials need to be alloyed in varying compositions.

The quality of a fabricated solar cell is primarily reflected in its overall efficiency. More detailed information about the operation of a solar cell can be obtained if a quantum efficiency (QE) measurement is performed. The QE of a solar cell device at a specified wavelength is defined as how many electrons contribute to the photogenerated current per incident photon. This extremely useful measurement of solar cell performance can be used to direct a cell improvement strategy.

This document describes research on amorphous, hydrogenated carbon as a potential semiconducting material for solar cells. Solar cell devices containing a-C:H have been fabricated using vacuum processes like thermal evaporation and reactive electric arc evaporation. The quantum efficiencies of several a-C:H solar cells have been measured to gain insight into the effectiveness of the photon conversion process.
2. Literature review

2.1. a-C:H for photovoltaic devices

Deposition of amorphous carbon films has been accomplished by a wide selection of techniques. Some of these techniques include deposition of a-C or a-C:H using ion beams [5], sputtering [6], plasma deposition [2] and cathodic arc evaporation [7]. In all of these methods, the source of carbon has been either graphite or a hydrocarbon gas (e.g. methane). The utilization of hydrocarbon gas results directly in hydrogenated carbon (a-C:H) films. If graphite is used as the source of carbon, additional hydrogen gas needs to be admitted to the vacuum system to produce a-C:H.

Several deposition parameters control the bandgap in a-C:H. One of these parameters is the kinetic energy of ionized particles impinging on the substrate surface. This kinetic energy in turn can be varied through the particle acceleration voltage (bias voltage). The effect of the bias voltage on the optical bandgap is shown in Figure 2-1A. An increase of bias voltage from 100 to 1000V leads to a decrease of the bandgap from about 2.1 to 1.0 eV. Another important deposition parameter is the substrate temperature. An increase in substrate temperature yields a-C:H films with decreasing bandgap (Figure 2-1B). The bandgap in a-C:H can be also controlled through the presence of hydrogen in the deposition system. An increase in molar H$_2$/Argon ratio during deposition of a-C:H causes widening of the bandgap (Figure 2-1C). This increase in bandgap width is attributed to two distinctive mechanisms. One of them is the passivation of dangling bonds by hydrogen, while the other mechanism is the hydrogenation of unsaturated bonds.
Figure 2-1:
Influence of deposition parameters on the optical bandgap in a-C:H, replotted from: A) [2], B) [8] and C) [9]
in a-C:H [9]. This is in contrast to a-Si:H where the incorporation of hydrogen leads only to a removal of dangling bonds.

The bandgap in amorphous carbon films can be substantially altered by a change in deposition parameters. Table 2-1 lists a selection of bandgaps obtained by different researchers using a variety of deposition techniques. A more comprehensive collection of data is given in reference [10]. It is important to note that many of these tabulated bandgap values do not represent achievable limits for the bandgap values, since the purpose of each study was different.

Table 2-1: Bandgaps of amorphous carbon reported by several researchers

<table>
<thead>
<tr>
<th>Bandgap [eV]</th>
<th>Deposition technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 - 2.0</td>
<td>plasma deposition from rf excited hydrocarbons</td>
<td>[2]</td>
</tr>
<tr>
<td>1.1 - 1.4</td>
<td>rf plasma beam and plasma assisted chemical vapor deposition</td>
<td>[11]</td>
</tr>
<tr>
<td>0.7 - 4.1</td>
<td>ion beam sputtering and plasma decomposition of methane</td>
<td>[3]</td>
</tr>
<tr>
<td>1.0 - 1.7</td>
<td>rf glow discharge from benzene</td>
<td>[12]</td>
</tr>
<tr>
<td>0.4 - 0.7</td>
<td>dc planar magnetron sputtering</td>
<td>[1]</td>
</tr>
<tr>
<td>2.1 - 2.4</td>
<td>cathodic arc with linear beam filter</td>
<td>[13]</td>
</tr>
</tbody>
</table>

Successful doping of amorphous, hydrogenated carbon is a requirement for more advanced solar cell structures. N-type and p-type doping of a-C and a-C:H with phosphorus (n-type), nitrogen (n-type) and boron (p-type) has been attempted by several
researchers [14, 15, 16]. The results from these studies in regard to a-C:H are contradictory and to date the prospect of doping this material remains unclear. N-type doping of a-C (86% sp³/14% sp²) with nitrogen and phosphorus is undisputed, however, attempts at doping the same material p-type with boron were not successful.

Concerning the fabrication of a-C:H based solar cell devices, the existing literature is rather limited. Very few heterojunction solar cell devices using a-C or a-C:H have been fabricated. US-Patent 5,206,534 held by Siemens AG, Germany describes the fabrication process of a-C:H/GaAs and a-C:H/InP heterostructures [17]. The same assignee holds US-patent 5,055,421 which relates to the production of a-C:H as a semiconductor base material [18]. Both patents involve a-C:H in its undoped form. Another group of researchers fabricated a heterojunction solar cell by depositing nitrogen doped, n-type a-C (86% sp³/14% sp²) on p-type crystalline silicon [19].
2.2. Quantum efficiency measurement

There is an abundance of publications concerned with the application of quantum efficiency measurements to semiconducting devices. Nevertheless, the development and refinement of quantum efficiency measurement methods itself is a subject that is rarely mentioned in the existing literature. According to a leading expert in the field of photovoltaic device measurements [20], no comprehensive review paper on quantum efficiency measurement techniques exists presently. Therefore, the following literature review is a mere attempt at citing some references in the field of quantum efficiency measurement methods. This review is not meant to be complete, nor is it claimed that the cited researchers are the first to develop a particular method. The evolution of quantum efficiency measurement methods certainly deserves a more rigorous treatment in a different publication.

The quantum efficiency measurement of electronic devices appears to be nearly as old as the discovery of photoconductivity. The first experimental observation of photoconductivity was in 1873 [21] when W. Smith observed a decrease in resistivity of selenium upon light exposure. Yet, it was not until 1905 when Einstein's explanation of the photoelectric effect allowed a clear understanding of phenomena like optical absorption, photoconductivity and the photovoltaic effect. Einstein's extension of Planck's quantum hypothesis proposed that light must be emitted in quanta or photons. The development of this photon theory paved the way for subsequent quantum efficiency measurements. Since photoconductivity was the precursor for more advanced electronic
device structures, early quantum efficiency measurements focused on photoconductive materials. Gradually, with the development of crystalline semiconductor devices, quantum efficiency measurements were extended to these devices. It should be mentioned here that the term 'quantum efficiency' is directly related to the term 'spectral response' since one can be converted into the other.

A more recent publication on quantum efficiency measurement techniques is given in reference [22]. This paper, written by Hartman and Lind, gives an overview of spectral response measurement systems and the problems associated with the measurement of particular types of solar cells. The authors conducted a laboratory survey to investigate the instrumentation and procedures that were commonly used for quantum efficiency measurements. The terminology of spectral responsivity, external and internal quantum efficiency was explained along with the procedure to obtain these quantities. Also, the advantages and disadvantages of using a chopped or unchopped illumination sources are discussed as well as the particular choice of a chopper.

A further publication concerned with quantum efficiency measurement techniques is a standard that was issued by the American Society for Testing and Materials (ASTM). This standard [23], with the designation E1021-84, was reapproved in 1993 and deals with test methods for measuring the spectral response of photovoltaic cells. These test methods are suggested to determine the absolute or relative spectral response of a single photovoltaic cell. The measurement techniques involve chopped, monochromatic light that is directed onto the test cell with subsequent lock-in amplification of the cell's output. In
addition to the chopped, monochromatic light, an unchopped source of white light is
directed toward the photovoltaic cell. This white light is referred to as bias light and its
purpose is to simulate actual outdoor operating conditions. It is further emphasized that
with respect to a linear cell response, the test cell needs to be operated under short-circuit
current conditions over the whole irradiance range used. Elsewhere, it is reported [24, 25]
that quantum efficiency values larger than unity can be obtained using a bias light during
the quantum efficiency measurement. This phenomenon was explained by a channeling
of bias-light-produced photocarriers into the modulated current response. For this reason,
no bias light was utilized for the quantum efficiency measurements of a-C:H based
devices which are described in this document.
3. Experimental methods and setup

3.1. Deposition system for the fabrication of a-C:H solar cells

The vacuum deposition technique that was used to deposit intrinsic a-C:H films was electric arc evaporation. Electric arc evaporation is a standard deposition method which has been used to make amorphous carbon coatings for many years. It is often preferred because of its inherent simplicity, but has the drawback that control of deposition rates is difficult to achieve. The electric arc evaporation technique used for this research was also a 'reactive' deposition method since hydrogen was deliberately introduced into the vacuum system. The deposited a-C:H was subsequently used to fabricate a-C:H based Schottky contacts and heterojunctions.

The electric arc evaporation system which was used to deposit a-C:H films was located within an 18" diameter bell jar (Figure 3-1). The bell jar was evacuated using an oil diffusion pump to a base pressure of approximately $1 \times 10^{-6}$ Torr. Subsequently, 10 standard cubic centimeters per minute (sccm) of ultra high purity hydrogen gas (99.999%) was introduced into the vacuum chamber by means of a mass flow controller. The diffusion pump was partially closed to obtain a hydrogen pressure in the range of 0.1-4.0 mTorr in the bell jar. Two tungsten boats for thermal evaporation of chromium and gold were positioned in the base of the vacuum chamber. In close proximity to these thermal evaporation sources, two high purity graphite rods (99.999%) were mounted. The distance between the graphite rods was adjusted from outside the vacuum chamber to start and maintain an electric arc. Alternating current supplied from a variable transformer was
passed through the graphite rods. The electric arc generated a plasma that contained charged and neutral carbon species. A water cooled substrate holder was mounted at about 25 cm above the graphite rods. The quartz crystal thickness monitor was in the vicinity of the substrate holder. An acceleration voltage of about -200 V was established between the graphite rods and the substrate holder. One of the graphite rods was grounded to obtain a reference for the plasma potential. Positive ions created in the plasma were then accelerated towards the negatively biased substrate holder. These accelerated ions impinged on the substrate and led to the formation of an a-C:H film. Successive film deposition of chromium, a-C:H and gold was made possible by a multiple mask changer which was an integral part of the substrate holder. The mask changer contained three different masks and one shutter and could be operated from outside the vacuum chamber.
3.2. Quantum efficiency measurement

3.2.1. Theory of quantum efficiency determination

ELEMENTARY KNOWLEDGE

As the term 'quantum efficiency' implies, it is the effectiveness of a quantum or many quanta in a specific process. With regard to photovoltaic devices, this specific process is the energy conversion of photon energy into electrical energy. In this case, the quantum efficiency is a measure of how well the photovoltaic device utilizes the quanta of light to generate an electric current. In other words, the quantum efficiency of a solar cell is defined as: how many electrons are generated per incident photon? Of course, the term 'quantum efficiency' can also be applied to an electroluminescence process. In an electroluminescent device, electrical energy is converted into photon energy. Here, the quantum efficiency refers to how well the electroluminescent device uses quanta of charge or electrons to emit light. In the following review of quantum efficiency theory, emphasis is given to photovoltaic devices.

The quantum efficiency of a photovoltaic device is measured on a macroscopic scale. Many photons of constant energy provide the radiant power that is incident on a photovoltaic device. Similarly, it is a multitude of electrons that constitute an electric current which is measured by an ammeter. Then, the number of generated electrons extracted from the measured current is divided by the number of photons obtained from the radiant power. The quotient is the quantum efficiency of the solar cell device for a constant photon wavelength.
The quantum efficiency curve of a solar cell device is measured under short-circuit conditions. There are two major reasons why this is necessary. The first reason is based on the original definition of the quantum efficiency, which is the number of electrons generated per incident photon. Any resistance connected to the two terminals of the solar cell device would impede the current flow. This decrease in current would result in lower quantum efficiencies measured. Therefore, only a very small shunt resistor on the order of less than 1/100 of the device resistance should be used to obtain a voltage drop that is proportional to the short-circuit current. Any other low input impedance circuitry that maintains the short-circuit conditions would also be acceptable. The second reason why the short-circuit condition is so important results from the incident light. Typically, the source of monochromatic light emits a number of photons that varies over several orders of magnitude in the measured wavelength range. Thus, it is important for an absolute quantum efficiency measurement that the tested device responds linearly to the incident number of photons. This linearity in cell response is best justified in the short-circuit condition.

There is a substantial difference between external and internal quantum efficiency. The external quantum efficiency is based on the total number of photons that are incident on the front surface of the device to be tested. Of course, some of these photons are reflected by the front surface of the device and thus, cannot contribute to the produced electric current. The loss of the reflected photons is incorporated in the internal quantum efficiency, which is based on the actual number of photons that penetrate into the solar cell device. Occasionally, quantum efficiency values are reported that refer only to a
particular absorbing layer (e.g. the intrinsic layer in a pin structure) in a multilayered device. To obtain such a value, adjustments need to be made to the originally measured quantum efficiency to account for absorption in prior layers. Although these internal versions of quantum efficiency are very helpful, the external quantum efficiency is also very important, since it reflects the overall performance of the device including a possible antireflection coating.

A further differentiation is made between absolute and relative quantum efficiency measurements. Absolute quantum efficiency values require the exact knowledge of how many photons are incident on the solar cell device. In addition, the exact number needs to be known of electrons generated by the device. In contrast to this, the relative quantum efficiency measurement allows an unknown, but constant offset in the number of photons. This is particularly of interest, if the number of photons are determined with an uncalibrated instrument that has at least a flat response over the required wavelength range. For convenience, the obtained relative quantum efficiency curve can be normalized with a quantum efficiency value at a selected wavelength.

**BASIC DETERMINATION OF QUANTUM EFFICIENCY**

The next part of the review explains how the number of incident photons is obtained for a given measurement situation. In Figure 3-2, two differing illumination situations are depicted. Figure 3-2A shows the illumination of a solar cell using a collimated, monochromatic light beam which is larger than the solar cell area. Figure 3-2B refers to a situation in which monochromatic light is focused onto a solar cell and in
Figure 3-2: Two methods of device illumination: A) collimated light exceeding the device area; B) focused light with spot size smaller than the device area which the focal spot size is smaller than the solar cell area. For both situations, it is important to observe that the radiant power $\phi$ in watts which is incident on the solar cell, is equal to the product of the irradiance $E$ in watts/cm$^2$ in the plane of the solar cell and the illuminated device area $A$ in cm$^2$ (Equation 3-1).

$$\phi = E \cdot A$$

(3-1)

For the collimated, monochromatic beam, the irradiance in the plane of the solar cell is determined by utilizing an instrument called a radiant power meter. The radiant power meter typically has a light sensitive detector area which is well known. In this case, the detector area is uniformly illuminated and the irradiance is the measured power divided by the detector area. Then, this irradiance is multiplied by the active solar cell device area to obtain the radiant power incident on the cell.
In contrast to this, the radiant power of the focused monochromatic light beam is more difficult to determine. Of course, again, a radiant power meter can be used. However, the detector area of the radiant power meter is most likely to be larger than the focused light beam. This presents a problem for the accuracy of the measured radiant power. Many detectors use a light diffusing element in front of their light sensitive area to minimize the effect of a small spot size. Nevertheless, an uncertainty in the radiant power measurement remains.

After the radiant power on the solar cell device has been determined, the radiant energy is known as well. The radiant energy $Q$ in Joules (Joules = Watts $\times$ seconds) is defined according to Equation 3-2 as the radiant power $\phi$ in watts multiplied by the time $t$ in seconds.

$$Q = \phi \cdot t \quad (3-2)$$

Substituting the expression for the radiant power $\phi$ in Equation 3-1 into Equation 3-2 results in the following expression for the radiant energy $Q$:

$$Q = E \cdot A \cdot t \quad (3-3)$$

Next, the radiant energy $Q$ needs to be related to the number of photons in the monochromatic light beam. One photon of wavelength $\lambda$ has the energy $hc/\lambda$, where $h$ denotes Planck's constant ($6.63 \times 10^{-34}$ Jsec) and $c$ is the speed of light ($2.998 \times 10^8$ m/sec). If the number of photons is $N_{\text{photon}}$, then a multitude of photons has the radiant energy $Q$ which can be written as:
Equation 3-3 and equation 3-4 are both expressions for the radiant energy $Q$. Elimination of $Q$ from these two equations results in:

$$Q = N_{\text{photon}} \cdot \frac{h \cdot c}{\lambda}$$  \hspace{1cm} (3-4)

Rearranging this equation gives an expression for the number of photons per time that arrive at the active solar cell area $A$:

$$N_{\text{photon}} \cdot \frac{h \cdot c}{\lambda} = E \cdot A \cdot t$$  \hspace{1cm} (3-5)

In this equation, the irradiance $E$ is a measured variable for which the value is obtained using a power meter. The illuminated solar cell area $A$ is known but depends on the type of illumination used. $\lambda$ is the wavelength of the monochromatic light, while $h$ and $c$ are constants.

To calculate the quantum efficiency of a solar cell device, the number of incident photons per time need to be known (Equation 3-6). Furthermore, the number of charge carriers which the device produces has to be determined. Therefore, an ammeter is connected to the device terminals and the short-circuit current $I_{\text{sc}}$ is obtained. The electric current $I$ in general is defined as the amount of electric charge $Q_{\text{el}}$ that passes a given point in a circuit during the time $t$:
If the charge $Q_{el}$ in Equation 3-7 is replaced by the number of electrons $N_{\text{electron}}$ multiplied by the electron charge $e$ ($1.602 \times 10^{-19}$ C), then the short-circuit current $I_{SC}$ can be written as:

$$I_{SC} = \frac{N_{\text{electron}} \cdot e}{t}$$  \hspace{1cm} (3-8)

Rearranging Equation 3-8 gives an expression for the number of electrons per time:

$$N_{\text{electron}} = \frac{I_{SC} \cdot e}{t}$$  \hspace{1cm} (3-9)

To calculate the quantum efficiency (QE), it shall be recalled that the quantum efficiency was defined as how many electrons are generated per incident photon. Thus, Equations 3-6 and 3-9 need to be combined resulting in the ratio of $N_{\text{electron}}/N_{\text{photon}}$, while the time $t$ cancels out:

$$QE = \frac{N_{\text{electron}}}{N_{\text{photon}}} = \frac{I_{SC} \cdot h \cdot c}{e \cdot E \cdot A \cdot \lambda}$$  \hspace{1cm} (3-10)

This is the equation for the quantum efficiency of a solar cell device at a single wavelength using the most basic experimental setup. Typically, a complete quantum efficiency curve is obtained for a photovoltaic device (Figure 3-3). For this purpose, quantum efficiency values at fixed wavelength intervals are recorded for a wavelength
range of about 300-1200 nm. The wavelength range of interest is determined by the onset of electric current generation in the UV region and the decay in the NIR region. Quantum efficiency values range from zero to one, assuming that a single incident photon can only excite one electron from the valence band into the conduction band, i.e. Auger recombination processes and trapping of electrons are not considered.

![Quantum Efficiency Curve](image)

**Figure 3-3:** Typical quantum efficiency curve for an amorphous, hydrogenated silicon (a-Si:H) single junction solar cell

**CALCULATION OF THE SHORT-CIRCUIT CURRENT DENSITY**

The calculated short-circuit current density for a typical a-Si:H single junction solar cell ($I_{sc}=13.8\text{ mA/cm}^2$) is also shown in Figure 3-3. This useful value is simply a back calculated value for a broadband illumination based on the measured quantum efficiency curve. Such as broadband illumination is usually a standard spectrum, for
example the standard global AM1.5 spectrum with an irradiance of 1000 W/m². In the ideal case, the calculated short-circuit current density based on QE measurements matches the short-circuit current density obtained from an I-V measurement under a solar simulator if the solar simulator matches the same standard spectrum and irradiance.

The standard global AM1.5 spectrum normalized to 1000 W/m² is published for example by the American Society for Testing and Materials (ASTM) under the designation E892-87 [26]. The data are tabulated as wavelength versus spectral irradiance values. The spectral irradiance \( E_\lambda \) has the units W/(m² μm) and is related to the irradiance \( E \) by the following equation, where \( \Delta \lambda \) is a small wavelength interval:

\[
E = E_\lambda \cdot \Delta \lambda
\]  

(3-11)

To calculate the short-circuit current density \( I_{sc}/A \) for a single small wavelength interval \( \Delta \lambda \), Equation 3-11 is substituted into Equation 3-10 and the expression is solved for \( I_{sc}/A \):

\[
\frac{I_{sc}}{A} = \frac{e}{h \cdot c} \cdot \Delta \lambda \cdot E_\lambda \cdot QE \cdot \lambda
\]  

(3-12)

The total short-circuit current density \( I_{sc, Density} \), however, is obtained by a summation over all wavelength intervals in the quantum efficiency curve:

\[
I_{sc, Density} = \frac{I_{sc}}{A} = \frac{e}{h \cdot c} \cdot \Delta \lambda \cdot \sum_{i=1}^{N} E_{\lambda_i} \cdot QE_i \cdot \lambda_i
\]  

(3-13)

In Equation 3-13, \( e, h \) and \( c \) are constants which were mentioned earlier, while \( \Delta \lambda \) is the
wavelength interval between successive quantum efficiency points in the measured curve. The parameters to the right of the summation sign are the spectral irradiance \( E_\lambda \) from a table and the quantum efficiency \( QE \) which was measured at the wavelength \( \lambda \). As an example, if the quantum efficiency of a device was measured at ten points wavelength points each 10 nm apart, then \( \Delta \lambda = 10 \text{ nm} \) and the summation is executed for ten terms, each of them evaluated for a different quantum efficiency point. If the total short-circuit current density \( I_{SC, Density} \) is calculated in mA/cm² and the wavelength interval \( \Delta \lambda \) is measured in nm, then Equation 3-13 can be simplified into:

\[
I_{SC, Density} = 8.0597 \times 10^{-5} \cdot \Delta \lambda \cdot \sum_{i=1}^{N} E_{\lambda_i} \cdot QE_i \cdot \lambda_i
\]  

(3-14)

In this equation, the spectral irradiance \( E_{\lambda_i} \) has units of W/m²μm and the wavelength \( \lambda_i \) is in μm.

**QUANTUM EFFICIENCY VERSUS SPECTRAL RESPONSE**

Quantum efficiency and spectral response measurements share the same experimental setup. However, the methods of evaluating the data are slightly different from each other. There are situations in which it is important to know how to convert quantum efficiency values into spectral response values and vice versa. For example the most current ASTM standard procedure for this type of measurement (ASTM E1021-84) [23] is in terms of spectral response rather than quantum efficiency. Figure 3-4 clarifies the difference between these two evaluation techniques. The quantum efficiency is the ratio of the number of electrons generated by the photovoltaic device per unit time to the
number of photons incident on the solar cell per unit time. The mathematical expression for the quantum efficiency was given in Equation 3-10, in which the quantum efficiency value thus has no unit. In contrast to this are spectral response values. The spectral response $R$ is the ratio of the short-circuit current in amperes produced by the photovoltaic device over the incident radiant power in watts. If the equation for the spectral response $R$ in Figure 3-4 is substituted into the Equation for the quantum efficiency $QE$, then a relationship between these two values is obtained:

$$QE = \frac{N_{\text{electron}}}{N_{\text{photon}}} \cdot \frac{I_{\text{SC}}}{E \cdot A}$$  \hspace{1cm} (3-15)

By inserting the values for the constants $h$, $c$, and $e$ into Equation 3-15, a handy expression is obtained to convert spectral response values into quantum efficiency values. In equation 3-16, the wavelength $\lambda$ is in nm while the spectral response is in A/W.
ADVANCED MEASUREMENT TECHNIQUES

To arrive at equation 3-10, a basic quantum efficiency measurement system has been discussed. The described system required using a power meter to determine the irradiance on the tested device. Instead of this power meter, a stable calibrated detector can be used for which the quantum efficiency curve is already known. This two step technique requires obtaining the test cell's short-circuit current first and directly after the calibration detector's short-circuit current. These measurements have to be done at each wavelength and in the same optical plane, which makes this procedure a little tedious. Nevertheless, the applicable equation for the quantum efficiency reduces to:

$$QE = \frac{1240.74}{\lambda} \cdot R$$  \hspace{1cm} (3-16)

If a shunt resistor is used to measure voltages rather than currents, Equation 3-17 is reformulated into Equation (3-18). The following treatment of advanced measurement techniques is in terms of measured voltages.

$$QE = \frac{I_{test\ cell}}{I_{cal\ det.}} \cdot QE_{cal\ det.}$$ \hspace{1cm} (3-17)

$$QE = \frac{V_{test\ cell}}{V_{cal\ det.}} \cdot QE_{cal\ det.}$$ \hspace{1cm} (3-18)

If one wants to avoid the multiple exchange of test cell and calibration detector, a beam splitter approach can be used. In this technique the original monochromatic light
beam is divided into two beams of monochromatic light. Both light beams are somewhat different in intensity and this difference is also a function of the wavelength. Next, an initial calibration needs to be done to establish the relationship between these two light beams. A stable reference detector with unknown quantum efficiency is placed in one beam, while the stable calibration detector is placed in the other light path. At each wavelength step in the region of interest, both detector voltages are recorded. These two detector voltages form a ratio that relates the two light beams:

\[
RATIO = \left( \frac{V_{\text{cal. det.}}}{V_{\text{ref. det.}} \text{ at cal. time}} \right)
\]  

(3-19)

Next, the calibration detector is taken out of the light beam. Nevertheless, it is still possible to predict what the calibration detector's voltage would be under any light conditions. This prediction is based on the reference detector voltage and the recorded voltage ratio that defines the relationship between the two light beams. Finally, the test cell is placed in the position that the calibration detector occupied previously. Now the actual measurement is taken at each wavelength step which includes the voltage of the reference detector and the test cell's voltage. The quantum efficiency of the test cell is then calculated according to:

\[
QE_{\text{test cell}} = \frac{V_{\text{test cell}}}{V_{\text{ref. det.}} \cdot \left( \frac{V_{\text{cal. det.}}}{V_{\text{ref. det.}}} \right) \text{ at cal. time}} \cdot QE_{\text{cal. det.}}
\]  

(3-20)
If there is no change in irradiance from the time of calibration to the time of measurement, then the reference detector voltages cancel out. The remaining equation is essentially the same as Equation 3-18. The advantage of this beam splitter approach is that the calibration for this system does not need to be done nearly as frequently as the previously discussed two-step technique.

Another variation of quantum efficiency measurements involves chopped, monochromatic light instead of a constant light source. This can also be incorporated into the beam splitter approach. The chopped light is incident on the solar cell device and produces an ac signal in the short-circuit current and thus in the measured voltage if a shunt resistor is used. This ac voltage is usually relatively small, so that a subsequent amplifier has to be used. This type of amplifier that can be synchronized with the chopper frequency is called a lock-in amplifier. The reference detector and the test cell each need a separate lock-in amplifier that produces a dc output voltage proportional to the ac input voltage. These output voltages from both lock-in amplifiers are similarly treated like the voltages obtained for constant light and Equation 3-20 applies. The use of chopped, monochromatic light has many advantages. Since only the ac portion of the measured voltages is amplified, the measurement system is relatively independent of stray light. The temperature rise of the test cell is less severe under chopped light than under constant light. The use of a chopped, monochromatic light is actually a necessity for the analysis of multijunction solar cells, but this will not be discussed here. There are also disadvantages to the use of chopped light. The chopper frequency often exceeds the response capabilities of the calibration cell and test cell, which leads to reduced ac
signals. The percentage of the voltage reduction is different for the calibration cell and the test cell. Already at a low chopper frequency, this behavior can cause a quantum efficiency measurement error of several percent.

The quantum efficiency measurement is a very useful tool for the optimization of solar cells. Nevertheless, the reader should be aware that the conditions under which the quantum efficiency is obtained are quite different from the actual operating conditions of a solar cell. For example, the quantum efficiency curve is measured with a monochromatic light beam, while real operating conditions for photovoltaic modules involve a broad spectrum of light. Cu$_2$S/CdS solar cells are a good example to elaborate on this point. Under chopped, monochromatic light, these cells show hysteresis effects in the quantum efficiency [27], while scanning from one wavelength to another. These hysteresis effects disappear and the quantum efficiency values are generally enhanced under simultaneous DC white light illumination. Based on these findings, the ASTM standard E1021-84 [23] recommends to use a DC white light bias of 700 W/m$^2$ irradiance in addition to the chopped, monochromatic light. It is suggested that this irradiance level should be used, unless it has been shown that the quantum efficiency becomes independent of the irradiance already at some lower irradiance level. On the other hand, recent publications [24, 25] suggest that DC bias light produces charge carriers that can be gated into the ac response of the cell causing a quantum efficiency larger than unity. Therefore, the quantum efficiencies of a-C:H based solar cells in this experimental study were performed using a beam splitter approach, however, a DC bias light was not utilized.
3.2.2. Quantum efficiency measurement system

The quantum efficiency measurement system can be divided into the optical setup (Figure 3-5) and the electrical setup (Figure 3-6). The optical setup contains a xenon arc lamp (1) that generates a broad spectrum of light. The light from this source is chopped (8) and focused onto the monochromator inlet slit. Monochromatic light exits the outlet slit of the grating monochromator (9) and is directed towards a filter wheel (10). The wheel slots accommodate a filter for the removal of undesired grating orders and also provisions to terminate the light beam or to let it pass. Monochromatic light passing through the filter wheel is refocused towards a partially transparent mirror (11). A fraction of the incident light beam is deflected by 90° while the remaining light passes through the

Figure 3-5: Optical setup for quantum efficiency measurement system
mirror. The deflected light beam is focused on a crystalline silicon reference detector (13), while the transmitted light beam encounters another partially transparent mirror (12). The reflected fraction of the incident light is lost, while the transmitted, monochromatic light is focused onto the test cell (15). In addition to the chopped monochromatic light (AC light), an unchopped light source (DC light) can be directed towards the test cell. The DC light from the tungsten light source (2) encounters an optional, interchangeable filter (14) as to select a particular pass band. The light beam transmitted through the filter is focused onto the partially transparent mirror (12). A fraction of the DC light is reflected from the partially transparent mirror and focused towards the test cell.

The electrical setup for the QE measurement system is shown in Figure 3-6. The crystalline reference detector is connected to an AC preamplifier which in turn provides the voltage input for the reference detector lock-in amplifier. Similarly, the test cell's AC voltage is preamplified before the signal enters the test cell lock-in amplifier input. The test cell preamplifier unit contains also an option to apply a DC bias voltage to the test cell. Both lock-in amplifiers (Stanford Research Systems SR530) receive their reference trigger signal from the chopper controller. The chopper controller is also used to adjust the frequency of the chopper. Both lock-in amplifiers produce a DC signal at their respective voltage outputs. These DC signals are fed into two A/D channels of a 12 bit multipurpose data acquisition card. The A/D conversion is controlled via Microsoft Basic as well as the digital input and output channels on the multipurpose card. The digital input/output channels allow computer control of the monochromator and the filter wheel. The monochromator drive consists of a stepper motor which is connected to the stepper
controller. The stepper controller receives its signals from the digital output channels on the DAQ card. The monochromator drive simultaneously rotates a multiple turn linear potentiometer which is used to provide a wavelength dependent voltage to an A/D channel. The filter wheel is rotated by a slow turning motor. For each window in the filter wheel, there is a corresponding notch at the circumference of the wheel. A spring loaded switch utilizes each notch to interrupt the motor action. The switch provides a digital input signal to the DAQ card. The filter wheel advances one position when the computer uses another digital output channel to momentarily override the switch. The two asynchronous serial communication ports of the computer are used to interface with both lock-in amplifiers. The major purpose of this computer control is to match the lock-in amplifier sensitivity to the input signal.

Figure 3-6: Electrical setup for quantum efficiency measurement system
The software for the quantum efficiency measurement system is written in Microsoft Basic. A listing for the complete program is provided in Appendix A. The majority of the software was developed prior to this work, therefore a general description of the program flow is given below. The author's work involved interfacing the computer with the RS232 ports of the lock-in amplifiers. This was done to adapt the lock-in amplifier sensitivity to the input signal voltage and ultimately led to a better reproducability of measurements. Therefore, those sections of the program which the author modified will be described in more detail.

On starting the program 'QAUTO.BAS', a menu of six choices appears on the screen. As shown in Figure 3-7, each choice is identified by a symbol. Pressing '1' will lead to an actual measurement of the quantum efficiency. '2' allows the operator to move the monochromator to any desired setting between 350 nm and 950 nm. Choice '4' is necessary to calibrate the system prior to an actual measurement. A calibrated detector of known quantum efficiency is used in this procedure. '3' allows the user to verify the calibration obtained in '4'. Choice '5' provides control over the filter wheel while 'Q' will

| QE Measurement                      | 1 |
| Set Monochromator                  | 2 |
| Check Calibration                   | 3 |
| Calibrate                           | 4 |
| Change Filter                       | 5 |
| Quit                                 | Q |

Figure 3-7: Main menu of quantum efficiency measurement software
exit the program.

For an actual QE measurement, the software initially reads the input files 'NAM1.5GL', ECDSTD.Q and 'VRCAL.RAT'. 'NAM1.5GL' is an input file that contains the irradiance versus wavelength data of the standard air mass 1.5 spectrum for global irradiation. 'ECDSTD.Q' contains the known QE values versus wavelength for the calibration detector. 'VRCAL.RAT' is an input file that was created during system calibration. This file contains a voltage ratio versus wavelength data. According to equation 3-19, the voltage ratio consists of the calibration detector voltage over the reference detector voltage at the time of calibration.

Next, the software prompts the user to select the type of solar cell to be analyzed. The choices are between a single, a tandem or a triple junction solar cell. The following description of the software will be restricted to the QE measurement of single junction solar cells as it applies to the fabricated a-C:H devices. After the type of solar cell has been selected, subroutine 'FindWindow' causes the filter wheel to move to the closed position. Subsequently, subroutine 'SetZeroOff' determines the offset voltages for both lock-in amplifiers in the 12 sensitivity ranges used. The 12 offset voltages for each lock-in amplifier are temporarily stored in a two-dimensional matrix, in which the first dimension denotes the lock-in amplifier number and the second dimension refers to the sensitivity range. The subroutine 'SetZeroOff' calls the function 'GETV' which triggers the data acquisition process.

After the offset voltages have been acquired, subroutine 'FindWindow' opens the
filter wheel and the user is prompted to verify the monochromator wavelength of initially 550 nm. Then, the subroutine 'SetMono' prompts the monochromator to move to 350 nm which is the starting wavelength for a single junction solar cell. Program control is given to subroutine 'WISwp' which causes the monochromator to move in about 10 nm steps from 350 nm to 950 nm. Subroutine 'WISwp' utilizes function 'VRATIO' which is responsible for acquiring the reference detector and test cell voltages during the actual QE measurement. Function 'VRATIO' also contains the logic which controls the sensitivity setting of the lock-in amplifiers. This logic verifies that each lock-in amplifier output voltage is always between 35-90% of the A/D channel input voltage range. If the lock-in amplifier output voltage sinks below 35%, the sensitivity of the corresponding lock-in amplifier is changed by sending a command through the respective computer serial communications port to the lock-in amplifier.

The reference detector and test cell voltages which are acquired during an actual QE measurement are divided to yield a voltage ratio. Together with the retrieved data from the input files 'VRCAL.RAT' and 'ECDSTD.Q', the quantum efficiency of the test cell is computed according to Equation 3-20. The calculated quantum efficiency values versus wavelength are displayed on the screen by subroutine 'QRgraf'. Function 'ISC' multiplies the QE values at each wavelength with the standard air mass 1.5 irradiance and integrates this over the wavelength range of 350-950 nm. This integration yields a calculated short-circuit current in mA/cm² which can be used as an estimate on how the solar cell device would perform under actual conditions. Finally, the QE values are stored in an output data file and the program returns to the main menu.
3.2.4. Calibration procedure

A calibration of this system is necessary because the actual measurement is essentially a comparison of a test cell's response to a calibrated standard cell's response. Furthermore, the calibration permits a correction for any light intensity change from the time of calibration to the time of an actual measurement. To calibrate the quantum efficiency measurement system, a stable photovoltaic device is used for which the quantum efficiency values as a function of wavelength are well known. Such a stable photovoltaic device for example is a crystalline silicon photovoltaic detector which will be referred to as the calibration detector. The known quantum efficiency values of this calibration detector are stored in the data file 'ECDSTD.Q'. There are 61 pairs of wavelength-quantum efficiency values in steps of 10 nm for the wavelength range of 350

![Figure 3-8: Quantum efficiency as a function of wavelength for the crystalline silicon calibration detector](image-url)
nm to 950 nm. Figure 3-8 shows the quantum efficiency of the calibration detector versus the wavelength.

This calibration detector is mounted in the position where otherwise the test cell would be located, so that the chopped monochromatic light is focused onto the detector surface. Then, the calibration detector is connected to the test cell preamplifier and the desired chopper frequency is selected. Software option '4' of the main menu initiates the calibration process, in which the lock-in amplifier output voltages of the reference detector and calibration detector are acquired. These voltages are recorded in steps of 10 nm from 350 nm to 950 nm. From the lock-in amplifier output voltages of the reference detector \( V_{\text{ref. det.}} \) and calibration detector \( V_{\text{cal. det.}} \) at each wavelength step, the software calculates the voltage ratio according to Equation 3-21.

\[
RATIO = \left( \frac{V_{\text{cal. det.}}}{V_{\text{ref. det. at cal. time}}} \right)
\]  

These voltage ratios are written to the data file 'VRCAL.RAT' which thus contains 61 data pairs of wavelength-ratio values. The creation of this data file concludes the calibration procedure.

Usually, the calibration is verified by using software menu option '3'. This option acts like a regular quantum efficiency measurement in that it determines the quantum efficiency of the calibration detector which is still located in the light path. The only exception is that this option displays the known quantum efficiency values of the
calibration detector on the screen together with the remeasured values. A typical example of a calibration check is shown in Figure 3-9. The solid line represents the known quantum efficiency values of the calibration detector, while the dotted line resulted from remeasured values during the calibration check. Figure 3-9 also shows the integrated short-circuit current which was obtained by the procedure detailed in Chapter 3.2.1. The deviation of the remeasured quantum efficiency values from the known values is less than one percent and shows the good repeatability of the calibration measurement.

\[ I_{sc} = 21.68 \text{ mA/cm}^2 \quad \text{(stored QE values)} \]
\[ I_{sc} = 21.67 \text{ mA/cm}^2 \quad \text{(remeasured cal. det.)} \]

Figure 3-9: Verification of system calibration by remeasuring the quantum efficiency of the calibration detector
3.2.5. Measurement procedure

After the calibration procedure is completed, the quantum efficiency of a test cell can be measured. This is done by placing the test cell as shown in Figure 3-5. The wavelength of the incident light is varied from 350 to 950 nm in 10 nm steps and the test cell lock-in amplifier's output voltage $V_{\text{test cell}}$ is recorded at each step. At the same time the reference detector lock-in amplifier's output voltage $V_{\text{ref. det.}}$ is recorded for each wavelength step as well. These two voltages ($V_{\text{test cell}}$, $V_{\text{ref. det.}}$) are called the actual time measurements, while the voltages taken during the calibration procedure are referred to as 'at calibration time'. The quantum efficiency of the test cell can be calculated using the following equation:

$$QE_{\text{test cell}} = \frac{V_{\text{test cell}}}{V_{\text{ref. det.}} \cdot \left(\frac{V_{\text{cal. det.}}}{V_{\text{ref. det.}}}\right)_{\text{at cal. time}}} \cdot QE_{\text{cal. det.}} \quad (3-22)$$

Substituting the expression for the voltage ratio into Equation 3-22 results in:

$$QE_{\text{test cell}} = \frac{V_{\text{test cell}}}{V_{\text{ref. det.}}} \cdot \frac{1}{RATIO} \cdot QE_{\text{cal. det.}} \quad (3-23)$$

This is the equation for the quantum efficiency which is utilized by the software during an actual measurement. The quantum efficiency values for the calibration detector are initially retrieved from the data file 'ECDSTD.Q9'. Similarly, the voltage ratio values which were written to the data file 'VRCAL.RAT' during calibration are retrieved initially.
4. Results and discussion

4.1. Characterization of a-C:H and fabricated devices

4.1.1. Absorption coefficients and bandgaps of a-C:H

To determine the absorption coefficients and the bandgaps of a-C:H films, a-C:H was deposited on 75 mm x 25 mm glass slides. The thickness of these a-C:H films ranged from 1000 to 3000 Å as measured by a mechanical profilometer (Dektak IIA). A two beam UV/VIS spectrometer (Cary 16) ranging from 300 to 800 nm was used to determine the attenuation of light by the a-C:H films. Evaluation of the absorption coefficient was performed according to the Lambert-Beer law, while multiple internal reflections were neglected. The bandgaps of a-C:H films were obtained by using the 'Tauc-plot' [28]. In all cases, the Tauc-plot yielded a fairly straight line which was extrapolated to the photon energy axis. At the intersection with the photon energy axis, the bandgap value was recorded.

The absorption coefficients of electric arc deposited a-C:H films are plotted in Figure 4-1. The five solid lines represent polynomial functions which were fitted to experimental data. Each of the solid lines is based on three separate a-C:H films fabricated under the same experimental conditions. For two of the fitted curves, the original data are shown. In this experimental study, the varied parameter was the hydrogen pressure in the vacuum chamber. The hydrogen pressure was maintained at 0.1, 0.5, 1.0, 2.0 or 4.0 mTorr during deposition of a-C:H.
The absorption coefficients of a-C:H films increase with photon energy. This behavior is consistent with the presence of a mobility gap in a-C:H, because for a fixed bandgap, the probability of electron transfer across the mobility gap rises with photon energy. However, at high photon energies (> 3.5 eV) the absorption coefficient becomes increasingly independent of photon energy. With increasing hydrogen pressure in the vacuum chamber, the absorption coefficients of a-C:H films decrease. This is due to a widening of the mobility gap as shown in Figure 4-2. In this figure, three bandgap values are plotted at each of five selected hydrogen pressures. Some of the bandgap values overlap each other. The solid line is a fitted function through the average bandgap at each hydrogen pressure. The largest change in bandgap width occurs for hydrogen pressures
in the range of 0.1 and 1.0 mTorr. This observation agrees with Figure 4-1 where the largest change in absorption coefficient occurs over the same hydrogen pressure range. However, it is important to realize that the experimental conditions chosen are representative only of a many parameter system. Therefore, the measured bandgaps do not represent achievable limits for the deposition system used.

![Figure 4-2: Tauc-bandgaps of electric arc deposited a-C:H films](image)
4.1.2. Low resistance contacts to a-C:H and fabricated devices

With the knowledge of required deposition conditions to obtain a specific bandgap in a-C:H, the next step was to find an ohmic contact to this material. The ohmic contact was needed for the back contact of future devices. Initially, graphite-, nickel- and silver-glue were used to attach two copper wires 1 mm apart to an a-C:H film. Devices made by this atmospheric contact method exhibited a linear I-V relationship although no photoconductivity was observed. Subsequently, glass/Cr/Au/a-C:H/Au sandwich structures were deposited in the vacuum chamber with gold and chromium being thermally evaporated. The chromium coating was necessary for improved adhesion of the gold layer. These sandwich structures showed also a linear I-V relationship and already displayed photoconductivity at low light levels. The ohmic contact was used for the back contact of each fabricated solar cell device.

To fabricate the Schottky and heterojunction devices, the multiple mask changer was used. This allowed the successive deposition of materials without interrupting the vacuum (Figure 4-3). The Schottky contacts were formed by successive deposition of chromium, a-C:H and gold on 75 mm x 25 mm microscope glass slides (VWR, 48300-036). The partially transparent chromium film (= 90 Å) was deposited over an area of 50 mm x 25 mm on the glass slide. Then, eight circles of a-C:H with about 8 mm in diameter were deposited on the chromium. The a-C:H circles were about 5000 Å thick. Finally, a back contact of about 470 Å gold was applied to the a-C:H pattern. This back contact had a circular shape with a diameter of about 5 mm. The heterojunction devices
Fabricated Schottky and heterojunction devices were fabricated in a similar manner to the Schottky contact. In the case of the ITO/a-C:H heterojunction device, however, the glass was already purchased (Donnelly, Kargo Ltd.) with an adherent coating of indium tin oxide (ITO). The Au/a-C:H/p type c-Si heterojunction device was obtained by depositing 1000 Å of a-C:H on a p-type crystalline silicon waver which had a resistivity of about 100 Ωcm. Then, a partially transparent gold
contact of 100 Å thickness was applied to the a-C:H. Table 4-1 lists the experimental conditions for the fabricated devices and the polarity of the obtained photovoltages. The different types of experiment are explained in more detail below.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Electric arc evaporation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt; 0.1 \text{ mT H}_2$</td>
<td>$2 \text{ mT H}_2$</td>
</tr>
<tr>
<td></td>
<td>$E_g = 0.4 \text{ eV}$</td>
<td>$E_g = 1.0 \text{ eV}$</td>
</tr>
<tr>
<td>glass/ITO (Donnelly)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>glass/ITO (Kargo Ltd.)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>glass/Cr</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 4-1: Polarity of obtained photovoltages; neg. lead of voltmeter at partially transparent front contact, pos. lead at back contact

Initially, ITO/a-C:H/Au heterojunctions were fabricated on 300 Å ITO coated glass (Donnelly Corp.). The a-C:H deposition was performed by electric arc evaporation at a hydrogen pressure of less than 0.1 mTorr. These devices consistently exhibited a photovoltage and photocurrent indicating a positive space charge in the a-C:H film and a negative space charge in the ITO layer. Consequently, photon generated conduction band electrons in the a-C:H film drifted towards the gold back contact. On a connected voltmeter, a negative voltage could be read. The proposed band diagram for this heterostructure is shown in Figure 4-4, in which the work function of ITO is taken to be 4.6 eV. ITO is a degenerate n-type semiconductor with the Fermi level being very close
BEFORE CONTACT:

\[
\begin{array}{c}
\text{VL} \quad 4.6 \text{ eV} \\
\text{CB} \quad 0.6 \text{ eV} \\
\text{FL} \quad 3.7 \text{ eV} \\
\text{VB} \quad \text{ITO}
\end{array}
\]

AFTER CONTACT:

\[
\begin{array}{c}
\text{ITO} \quad \text{a-C:H} \\
\text{a-C:H} \quad \text{Au}
\end{array}
\]

Figure 4-4: Proposed band diagram for ITO (Donnelly Corp.)/a-C:H/Au contact; a-C:H was deposited at a hydrogen pressure < 0.1 mTorr.

to the conduction band. The work function of a-C:H is estimated to be about 4.4 eV based on the magnitude of the obtained photovoltage. The Fermi level in a-C:H is assumed to be in the middle of the bandgap since literature is not available on its intrinsic majority carrier type. The work function of gold is about 5.1 eV. The proposed band diagram suggests a depletion region at the ITO/a-C:H interface with valence band and conduction band offsets. The a-C:H/Au interface is expected to act as an ohmic contact due to a hole accumulation layer.

Following the fabrication of these initial heterojunctions, 1600 Å ITO coated glass from an alternate company was purchased (Kargo Ltd.). Using electric arc evaporation at a hydrogen pressure of less than 0.1 mTorr, ITO/a-C:H/Au heterojunctions were then fabricated from this new supply of conducting glass. These devices exhibited a photovoltage opposite in polarity to previous devices. The explanation of this peculiar
behavior can be understood by examining the Fermi level in ITO. Since ITO is a degenerate n-type semiconductor, the Fermi level is in close proximity to the conduction band edge. However, the position of the Fermi level is also characterized by the ITO oxidation state which varies among vendors. Thus, the work function of ITO is generally about 4.5 eV but varies with oxidation state. The observed polarity change was therefore caused by an ITO work function which was slightly smaller than that of a-C:H. The conclusion which can be drawn from this argument is that the work function of these particular a-C:H films was similar to the work function of ITO, which is approximately 4.5 eV.

Electric arc evaporated a-C:H films at a hydrogen pressure of < 0.1 mTorr were further used to obtain glass/Cr/a-C:H/Au Schottky contacts. The negative polarity of the obtained photovoltages suggest a work function of a-C:H which is at least smaller than the one for chromium. Since chromium has a work function of 4.5 eV, the value for a-C:H is estimated to be about 4.4 eV. This value should be more precise than the estimate obtained from ITO experiments. However, the work function of 4.4 eV for a-C:H applies only for films deposited at a hydrogen pressure of < 0.1 mTorr. More experiments were done at an increased hydrogen level of 2 mTorr by electric arc evaporation. ITO/a-C:H/Au heterostructures fabricated on conducting glass from both vendors exhibited positive photovoltages. The same result was obtained for the Cr/a-C:H/Au Schottky contacts. These results indicate that the work function of a-C:H films increases with increasing hydrogen pressure in the vacuum chamber.
The proposed band diagram for the Schottky contact which was fabricated at a hydrogen level of 2 mTorr is shown in Figure 4-5. In this diagram, the work function of chromium is taken to be 4.5 eV while the a-C:H work function is estimated to be about 4.6 eV. At the Cr/a-C:H interface, the positive space charge is located in the chromium layer while the negative space charge appears in a-C:H. Photon generated conduction band electrons are attracted by the resulting internal field and are directed towards the partially transparent chromium layer. A voltmeter connected with the negative lead to the chromium layer and the positive lead to the Au back contact thus displays a positive photovoltage.

The a-C:H/p type c-Si heterojunction devices were obtained by depositing 1000 Å of a-C:H on p type crystalline silicon wafers which had a resistivity of about 100 Ωcm. The a-C:H layer was deposited using a hydrogen pressure of 0.75 mTorr in the vacuum

Figure 4-5: Proposed band diagram for Cr/a-C:H/Au contact; a-C:H was deposited at a hydrogen pressure of 2 mTorr
chamber. These experimental conditions were expected to produce a-C:H with a bandgap of about 0.8 eV. This heterojunction device was completed by depositing a 100 Å partially transparent gold contact onto the a-C:H layer. Light entered the device through the partially transparent front contact and the observed photovoltage indicated a positive space charge in the a-C:H layer and a negative space charge in the p type c-Si. Thus, photoexcited electrons in the conduction band of p type c-Si were attracted by the internal electric field and drifted in the direction of the partially transparent front contact. Consequently, a voltmeter with the negative lead connected to the partially transparent gold contact and the positive lead connected to the p type c-Si displayed therefore a positive open-circuit voltage. The suggested band diagram for this device is shown in Figure 4-6. The potential energy diagram shows clearly the decrease of potential energy and the increase in kinetic energy for conduction band electrons that move through the internal electric field. The partially transparent gold layer acts here as an ohmic contact.

![Figure 4-6: Proposed band diagram for Au/a-C:H/p type c-Si heterojunction device](image-url)
due to a hole accumulation layer at the Au/a-C:H interface.

The fabricated devices were illuminated with a xenon arc lamp at a power density of approximately 800 W/m². Each cell had an active area of about 0.5 cm². The Cr/a-C:H/Au Schottky contacts produced open-circuit voltages of up to 150 mV and a short-circuit current of about 0.2 μA. The Au/a-C:H/p type c-Si heterojunction generated $V_{oc} = 200$ mV and $I_{sc} = 1.4$ μA. The ITO/a-C:H/Au heterostructure exhibited typically an open-circuit voltage of 50 mV and a short-circuit current of about 0.5 μA.
4.2. Quantum efficiency measurement of fabricated devices

4.2.1. Determination of the appropriate chopper frequency

A solar cell that has been subjected to light at the time \( t_1 \), needs a finite rise time \( \Delta t_R \) until the short-circuit current \( I_{sc} \) becomes fully established. Similarly, after the light is shut off at the time \( t_2 \), a decay time \( \Delta t_D \) passes before the short-circuit current equals zero (Figure 4-7).

![Figure 4-7: Schematic diagram of the short-circuit current versus time for a solar cell subjected to a pulsed light source](image)

Now it shall be discussed what happens, if the time interval \( t_2 - t_1 \) gets decreased. As is shown in Figure 4-8, the short-circuit current \( (I_{sc}) \) rises after the light pulse hits the solar cell at time \( t_1 \). At time \( t_2 \), the light pulse duration ends while \( I_{sc} \) is not yet fully established. This behavior will always be present, when the light pulse duration is shorter than the solar cell rise time. At time \( t_2 \), the short-circuit current starts to decay and \( I_{sc} \)
would approach zero if there would be sufficient time. However, since the dark pulse
duration is also shorter than the decay time of the solar cell, \( I_{sc} \) will rise yet again before
zero is reached.

![Figure 4-8: Schematic diagram of the short-circuit current versus time for a solar cell
subjected to a pulsed light source at high pulse frequency](image)

The consequence of a high chopper frequency which exceeds the response
capability of a solar cell, is a decreased alternating signal for the test cell preamplifier
input. If the chopper frequency is increased even more, the rise of \( I_{sc} \) and its decay are
interrupted even sooner. This results in an even smaller AC signal for the preamplifier
input and ultimately for the lock-in amplifier. The lock-in amplifier generates a DC
voltage at its output which is proportional to the AC signal amplitude at its input. The
expected lock-in amplifier output voltage as a function of chopper frequency is shown in
Figure 4-9.
As was said earlier, the measured QE is essentially determined by the ratio of the test cell voltage over the calibration detector voltage. Thus, a decreased test cell voltage due to a high chopper frequency results in lower than the 'true' QE values. The situation is even more complicated since both, the calibration detector and the test cell have their own response time. Two cases can be imagined which are illustrated in Figure 4-10. In the first case, the normalized lock-in amplifier output voltage of the calibration detector falls faster than the normalized lock-in amplifier output voltage of the test cell for increasing chopper frequency. For any chopper frequency higher than the minimum frequency in Figure 4-10A, the QE values will be overestimated. This is because a progressively smaller test cell voltage is sufficient to yield the same voltage ratio \( \frac{V_{\text{test cell}}}{V_{\text{calibration detector}}} \) that prevails at the minimum chopper frequency. Similarly, Figure 4-10B shows the second case which leads to an underestimate of QE values. There, the
normalized test cell voltage falls faster than the normalized calibration detector voltage for all chopper frequencies larger than the minimum frequency.

This argumentation undoubtedly leads to the question why not to measure at the minimum chopper frequency. The minimum chopper frequency which will not exceed the test cell response speed, is often significantly less than about 5 Hz. In contrast to this, a lock-in amplifier does not perform well at these low frequencies. In general, the higher the chopper frequency, the lower is the noise which affects the lock-in amplifier output voltage. Thus, the actual chopper frequency is often a compromise between these two issues. Nevertheless, after a chopper frequency has been selected, the mismatch in frequency response between the test cell and the calibration detector needs to be accounted for by a correction factor.
To determine the appropriate chopper frequency, graphs similar to Figure 4-10 were obtained for the actual calibration detector and test cell (Figures 4-11 and 4-12). The data for these graphs were acquired by essentially using the same experimental setup which was used for quantum efficiency measurements. Either the calibration detector or test cell were connected to the preamplifier while the preamplifier in turn provided the AC voltage for the lock-in amplifier input. Chopped, monochromatic light was incident on the calibration detector or test cell. Then, the lock-in amplifier DC output voltage was recorded at equally spaced chopper frequencies. Each measurement that was taken was repeated five times to quantify the experimental error. Measurements were performed for the calibration detector which was a crystalline silicon photovoltaic device and for an amorphous, hydrogenated carbon (a-C:H) photovoltaic test cell. It shall be noted that none

Figure 4-11: Normalized lock-in amplifier output voltage versus chopper frequency for the c-Si calibration detector at monochromatic light of 450 nm and 650 nm
of the lock-in amplifier's input filters, e.g. line frequency notch filters, were active during these measurements since their bandwidth of about 20 Hz modifies the test cell's response significantly.

Figure 4-11 displays the chopper frequency versus the normalized lock-in amplifier output voltage for the crystalline silicon calibration detector. The upper graph was obtained for chopped light of 450 nm while the lower graph was acquired at a wavelength of 650 nm. These two wavelength have been selected because it cannot be simply assumed that the response of a tested device for chopped light is independent of photon energy. However, both curves show a continuous decrease of lock-in amplifier output voltage with increasing chopper frequency as is expected for a slow acting device. In the chopping frequency range from 5 Hz to 160 Hz, the lock-in amplifier output voltage decreases about 8%. A comparison of the curves at 450 nm and 650 nm leads to the conclusion that any deviation between these two curves is within the experimental error. Thus, at the measured chopper frequencies, there is no apparent dependency of the lock-in amplifier output voltage on the wavelength of the incident light. A further observation is that the minimum chopping frequency of 5 Hz is already higher than the response speed of the tested device.

An amorphous, hydrogenated carbon photovoltaic test cell was subjected to the same type of measurement. However, since the a-C:H cells in general exhibited a very small response to chopped light, the wavelength at which the highest response occurred was determined. The highest response of a-C:H cell occurred typically for incident light
of about 370 nm and therefore this wavelength was selected to perform chopper experiments. Figure 4-12 shows the chopper frequency versus the normalized lock-in amplifier output voltage for the a-C:H test cell. The normalized lock-in amplifier output voltage decreases with increasing chopper frequency. This amounts to a voltage drop of approximately 20% for the chopper frequency interval of 5 Hz to 160 Hz.

![CHOPPER FREQUENCY (Hz)](image)

**Figure 4-12:** Normalized lock-in amplifier output voltage versus chopper frequency for the a-C:H test cell at incident monochromatic light of 370 nm

From Figure 4-12 it can be seen that the experimental error for measuring an a-C:H test cell is relatively small for a chopper frequency of 90 Hz. This was the primary reason, why this frequency was then selected for measuring the quantum efficiency of a-C:H solar cells. Supporting this decision was that the chopper frequency needed to be outside the interval of 40 Hz to 80 Hz because the line frequency notch filter which was centered at 60 Hz would have significantly diminished the already small solar cell output voltage. A comparison between Figure 4-11 and Figure 4-12 shows that at a chopper
frequency of 90 Hz, the normalized lock-in amplifier output voltage of the a-C:H solar
cell is about 5% smaller than the one of the calibration detector. In analogy to Figure 4-
10B this resulted in measured quantum efficiencies of a-C:H cells that were 5% lower
than the 'true' values. As it will be shown later, measured quantum efficiency values of
a-C:H solar cells are very small compared to solar cells made from conventional
semiconducting materials. Therefore, no correction factor was used at this time to account
for the 5% lower than the 'true' a-C:H quantum efficiency values.
4.2.2. Verification of operation in the linear short-circuit current regime

The calibration detector that was used for the quantum efficiency measurement system was calibrated by a different laboratory. Therefore the quantum efficiency curve for this calibration detector was known, however, the radiant power at which these values were measured was not obtainable in this particular case. To explain the significance of this radiant power level, Figure 4-13 shows a schematic in which the lock-in amplifier's DC output voltage is shown as a function of the incident radiant power for a hypothetical calibration detector. The condition at which this hypothetical detector was calibrated is represented by the solid circle. The dashed vertical line intercepts the horizontal axis, at which the radiant power at the time of calibration can be found. The horizontal dashed line intercepts the vertical axis, which is the corresponding calibration detector's lock-in amplifier output voltage. A properly calibrated detector would exhibit a linear relationship between the irradiant power and the lock-in amplifier DC output voltage at least up to the

![Figure 4-13: Schematic showing the response of the calibration detector as a function of the incident radiant power](image-url)
radiant power level used for calibration. This linear relationship is represented by the solid line from the origin to the solid circle. If the quantum efficiency measurement of a test cell is performed at a higher irradiant power level than the one used for calibrating the calibration detector, then it needs to be verified that the solid line in Figure 4-13 extends linearly. The significance of this is that if the solid line extends less than linear, this behavior would lead according to Equation 3-18 to an overestimate of measured quantum efficiencies. The same argumentation can be applied toward the test cell. The radiant power level needs to be chosen, so that the test cell's lock-in amplifier DC output voltage is linearly related to the radiant power. Any lock-in amplifier output voltage that is in a less than linear relationship to the irradiant power will result in underestimated quantum efficiency values.

The linearity of the lock-in amplifier's response versus the irradiant power was tested for the c-Si calibration detector and a representative a-C:H based device. The c-Si calibration detector was illuminated with chopped, monochromatic light at 450 nm and in a further measurement at 650 nm. The choice of these two wavelengths was in response to the wavelength dependent photon flux emitted by the xenon arc lamp. The a-C:H based device was a ITO/a-C:H/Au heterojunction which was illuminated with chopped, monochromatic light of 380 nm. This particular wavelength was selected because the a-C:H based devices exhibited in general a very small photovoltaic response which typically had its peak at about 380 nm. During these irradiant power versus lock-in response measurements, the chopper frequency was at 90 Hz which was the same frequency used for measuring the quantum efficiency of a-C:H based devices.
Figure 4-14 shows the results of these measurements for the crystalline silicon calibration detector. By using a power meter, the irradiant power was adjusted to 0.3, 0.5, 0.7, 0.9 and 1.1 μW for each of the two measured wavelengths. Of course, this means that at 650 nm there was a higher number of photons per time arriving at the c-Si calibration detector than at 450 nm. This fact, along with the higher quantum efficiency of the calibration detector with increasing wavelengths resulted in a generally higher lock-in response at 650 nm than at 450 nm. For each of the two wavelength and at each irradiant power level, five repeated lock-in amplifier output voltage values were recorded to estimate the experimental error. The averaged experimental data can be fitted with a straight line at 450 nm and 650 nm. Thus, it is verified that the c-Si calibration detector operates in the linear short-circuit current regime for at least the irradiant power range of 0.3 to 1.1 μW.

Figure 4-14: Lock-in amplifier output voltage versus radiant power for the c-Si calibration detector
The results of the lock-in amplifier output voltage versus the radiant power for the a-C:H based device are shown in Figure 4-15. The irradiant power at 380 nm which the instrument could produce was substantially less than at 450 nm or 650 nm. The lock-in amplifier's output voltage was recorded at irradiant power levels of 0.06, 0.09, 0.12, 0.15 and 0.177 μW. Each measurement was repeated five times to quantify the experimental error. Compared to the c-Si calibration detector, the ITO/a-C:H/Au heterojunction produced a much lower response to the incident light. Therefore, the lock-in amplifier range was switched to a more sensitive setting in the microvolt range. From Figure 4-15 it can be seen, that the experimental error is substantially larger when compared to the c-Si calibration detector. This is mainly caused by the more sensitive lock-in amplifier setting which also amplifies noise. Nevertheless, the measured data points can be fitted with a straight line which is essential for subsequent quantum efficiency experiments.

![Figure 4-15: Lock-in amplifier output voltage versus radiant power for the ITO/a-C:H/Au heterojunction device](image)
4.2.3. Repeatability of quantum efficiency measurements

The repeatability of nearly every scientific measurement is a paramount factor for the trustworthiness of acquired data. Thus, the evaluation of quantum efficiency versus wavelength curves is critically dependent on the repeatability of obtained data. A poor repeatability of quantum efficiency values not only results in false short-circuit current calculations, but can also lead to misinterpretation of experimental data. Therefore, a repeatability test of the quantum efficiency measurement system was conducted before any modifications to the system were done. The repeatability test involved five measurements of the quantum efficiency curve for a single junction a-Si:H solar cell. These five quantum efficiency curves are displayed in Figure 4-16.

Figure 4-16: Quantum efficiency versus wavelength curve repeated five times for an a-Si:H single junction solar cell
From Figure 4-16 it is apparent that the QE measurement system had a poor reproducability in the 350-380 nm region. In this wavelength region, the measurement system produced an artificial peak which could have led to misinterpretation of research results. In addition, since the short-circuit current is calculated using the area under the QE curve, the short-circuit current is also affected by this artificial peak. The poor reproducability was caused by lock-in amplifier sensitivity settings which were not properly matched to the signal magnitude at the lock-in amplifier inputs. This problem was corrected within the scope of this research as a preparation for measuring a-C:H based solar cell devices. Two communication lines were subsequently connected between the computer and both lock-in amplifiers. These communication lines and the associated software allowed the computer to automatically change the sensitivities on both lock-in amplifiers to the appropriate settings independently from each other.

A further modification was done to the data acquisition software because the settling time which precedes the data logging was found to be a fixed settling time which in addition was too short. After the monochromator has been moved to its new wavelength, mainly the lock-in amplifiers need a settling time until their DC output voltages become stable. This settling time is especially affected by the time constant of the lock-in amplifier filter. A further factor which determines the settling time is the variation in light intensity from one wavelength step to another. The xenon arc light source has a spectral distribution which exhibits several peaks in the near infrared region. If such a peak is encountered directly after the monochromator moved to the next wavelength, the lock-in amplifiers need several seconds to stabilize their DC output.
voltages. Finally, the added computer control of the lock-in amplifiers sensitivity settings made it absolutely necessary to implement a variable settling time. Whenever the computer detects the need for a change in sensitivity setting, the setting is changed and the lock-in amplifiers output voltages are monitored until their stability meets a predetermined criterion.

After these modifications were made to the quantum efficiency measurement system, the fabricated a-C:H based solar cell devices could be measured. The improvements to the measurement system were a crucial step because the fabricated a-C:H based devices showed substantially lower quantum efficiency values than a-Si:H photovoltaic cells. With the improvements to the measurement system, another repeatability study was conducted in order to quantify the experimental error involved in measuring the quantum efficiency of a-C:H based solar cells. The quantum efficiency curve of a fabricated ITO/a-C:H/Au heterojunction was measured five times. The result of these measurements is shown in Figure 4-17, where the error bars indicate the standard deviation of the sample population. The open squares represent the average of five quantum efficiency values at each wavelength step. The short-circuit current for this particular device was calculated to be $1.018 \pm 0.037 \mu A/cm^2$ which is definitely the order of magnitude which was measured under a light source with a spectrum of AM1.5 global at 1000 W/m$^2$.

From Figure 4-17 it is evident that the experimental error increases from the near infrared to the ultraviolet region. This is probably due to the c-Si reference detector
voltage which is very small in the UV region. This small voltage with its associated error enters the quantum efficiency formula (Equation 3-18) in the denominator and thereby causes a relatively large experimental error in the UV region. This is in contrast to the very small a-C:H based test cell voltage in the near infrared region. The small test voltage has also an associated error but enters the quantum efficiency formula in the numerator and thereby causes a smaller experimental error when compared to the situation in the UV region.
4.2.4. Quantum efficiency of selected a-C:H solar cells

The quantum efficiency curves for several types of a-C:H based solar cells were obtained at the appropriate chopper frequency, which was determined to be 90 Hz. In addition, the operation in the linear short-circuit current region was verified for the test cell and the calibration detector. The first device for which the quantum efficiency curve was determined was an ITO/a-C:H/Au heterojunction solar cell. The ITO layer on glass (Donnelly) had a thickness of about 300 Å, while the a-C:H layer was about 5000 Å thick. The a-C:H was deposited in the vacuum chamber at a hydrogen pressure of about 0.1 mTorr to yield a bandgap of approximately 0.4 eV. A back contact of 470 Å of gold was deposited onto the a-C:H layer. This device exhibited a polarity in photovoltage suggesting a negative space charge in the ITO and a positive space charge in the a-C:H layer. The quantum efficiency curve for this ITO/a-C:H/Au heterojunction solar cell is shown in Figure 4-18. At the shortest wavelength of 350 nm, the quantum efficiency is about 0.044 % and rises to its maximum of about 0.064 % at 380 nm. For longer wavelength than 380 nm, the quantum efficiency curve decays exponentially. The generally very low quantum efficiency values can be explained by a device resistance which was on the order of one megaohm and thus limited the short-circuit current. Photons with a wavelength below the quantum efficiency maximum at 380 nm are preferentially absorbed in the front of the ITO layer before they ever reach the active ITO/a-C:H junction. These high energy photons do not contribute to the photogenerated current and determine the shape of the quantum efficiency curve below 380 nm. With increasing wavelength, an increasing number of photons reaches the active junction which
results in the peak quantum efficiency at 380 nm. It is quite interesting to note that the photon energy of 3.26 eV corresponding to 380 nm is substantially larger than the measured Tauc bandgap of the a-C:H layer which was approximately 0.4 eV. This difference in Tauc bandgap and the photon energy at the maximum quantum efficiency response could be explained with the density of states in a-C:H. Electric arc deposited a-C:H contains usually a high fraction of sp² hybridized carbon atoms resulting in many localized states in the bandgap. A sufficient density of these localized states could provide an efficient recombination path for excited electrons in the conduction band to the valence band. If this phenomenon occurs in the positive space charge region in a-C:H, then only high energy photons which transfer electrons into the extended sp³ states would contribute
to the photocurrent. Photons of wavelength larger than 380 nm result in an exponential decaying quantum efficiency curve for two reasons. The first reason is based on the fact that longer wavelength photons are increasingly unable to excite valence band electrons into the extended states. The second reason is that the absorption coefficient decreases with increasing wavelength. Therefore, a longer path length is necessary to absorb photons of wavelength longer than 380 nm. Consequently, since diffusion is not effective in this amorphous material, these photons are essentially lost to the photocurrent which is reflected in the decaying tail of the quantum efficiency curve. The integrated short-circuit current amounted to 2.421 μA/cm². This calculated current is very close to the actual measured short-circuit current of 0.5 μA, if one considers that the active surface area of fabricated cells was about 0.5 cm² and the irradiance was only 800 W/m² compared to 1000 W/m² used for the calculation.

A further quantum efficiency curve was obtained for a Cr/a-C:H/Au Schottky device. The partially transparent front contact consisted of 90 Å of chromium deposited on glass. The next layer of a-C:H was about 5000 Å thick with a-C:H deposited at a hydrogen pressure of 2 mTorr in the vacuum chamber. These conditions typically led to an a-C:H bandgap of about 1.0 eV. A gold back contact of 470 Å was applied to the structure. The observed photovoltage indicated a negative space charge layer in the a-C:H and an extremely thin positive space charge layer in the chromium. The quantum efficiency curve for this device is shown in Figure 4-19. From this figure it is apparent that the quantum efficiency values are in general very small. This is typical for a high impedance device, since the impedance for Cr/a-C:H/Au contacts were on the order of
Figure 4-19: Quantum efficiency curve for a Cr/a-C:H/Au Schottky contact

several megaohms. The quantum efficiency at 350 nm is about 0.010 % and rises to the maximum of 0.019 % at 360 nm. For longer wavelength, the quantum efficiency curve decays exponentially. For the Cr/a-C:H/Au Schottky contact, the same arguments apply that were discussed to explain the shape of the quantum efficiency curve for the ITO/a-C:H/Au device. Nevertheless, a comparison of the quantum efficiency curves of these two devices shows that the Schottky contact has its maximum quantum efficiency at a shorter wavelength than the heterojunction. This is because the partially transparent chromium contact of the Schottky contact is substantially thinner than the transparent conductive oxide layer of the heterojunction. Comparingly less photons of shorter wavelength are absorbed in the chromium and can therefore contribute to the photogenerated current in
the a-C:H layer. The calculated short-circuit current of 0.581 µA/cm² for an irradiance of 1000 W/m² is consistent with the measured short-circuit current of about 0.2 µA at 800 W/m² for an active device area of 0.5 cm².

The quantum efficiency curve for a different Au/a-C:H/p-type c-Si heterojunction device was measured. This heterojunction was fabricated by depositing a-C:H on a wafer of p-type c-Si that had a resistivity of about 100 Ωcm. The a-C:H layer of 1000 Å thickness was produced with 0.75 mTorr hydrogen in the vacuum chamber so as to obtain a material with a bandgap of approximately 0.8 eV. A partially transparent gold contact of 100 Å thickness was coated onto the a-C:H layer. From the polarity of the photovoltage it was deduced that a positive space charge was present in the a-C:H layer, while a negative space charge resided in the crystalline silicon. The quantum efficiency curve for this device is presented in Figure 4-20. The general shape of the quantum efficiency curve is fundamentally different from the previously discussed devices. The quantum efficiency at 350 nm is 0.12 % and rises monotonically to about 1.8 % at 860 nm. These quantum efficiency values are higher than the ones of previously discussed devices. This is because a-C:H contributes somewhat to the photocurrent but it is the crystalline silicon that is the 'workhorse' in this device. The a-C:H layer enables a space-charge region to develop, but also absorbs many photons before they ever reach the active junction. Remembering the absorption coefficient of a-C:H as a function of wavelength, it is therefore not surprising that the quantum efficiency for this device increases with wavelength. Eventually, a maximum is reached at longer wavelengths before a dropoff is encountered based on the 1.1 eV bandgap of crystalline silicon. The integrated short-
Figure 4-20: Quantum efficiency curve for a Au/a-C:H/p-type c-Si heterojunction solar cell device

circuit current for this particular device is not comparable to the measured value because the long wavelength quantum efficiency tail was not measurable.
5. Conclusions & Recommendations

Amorphous, hydrogenated carbon (a-C:H) films were deposited by 'reactive' electric arc evaporation. The deposited a-C:H films have Tauc bandgaps in the range of 0.3-1.1 eV. The vacuum application of gold or the atmospheric application of graphite-, nickel- or silver-glue to a-C:H was found to yield ohmic contacts. ITO/a-C:H/Au and Au/a-C:H/p type c-Si heterostructures as well as Cr/a-C:H/Au Schottky contacts were fabricated. The change in polarity of obtained photovoltages indicates a work function of about 4.4 eV for a-C:H produced at low hydrogen pressure. With increased hydrogen pressure during the deposition of a-C:H, the work function of a-C:H rises simultaneously with its bandgap. This leads to the conclusion that the Fermi level in a-C:H is not pinned by defects at the interface.

The fabricated devices yield an open-circuit voltage of up to 200 mV and a short-circuit current of in the range of 0.1-1.4 μA. These values were obtained using a xenon arc lamp at a power density about 800 W/m² for an active cell area of about 0.5 cm². This low short-circuit current is due to a high internal resistance in the range of 0.5-30 MΩ. Upon exposure to the atmosphere, the devices experience an increase in resistance which is probably due to oxidation of the metallic films. Even though the resistance of fabricated devices drops approximately 80% under illumination, the remaining resistance limits the short-circuit current.

A quantum efficiency measurement system was used to analyze the fabricated solar cell devices. Prior to the actual measurements of a-C:H based devices, the quantum
efficiency measurement system was substantially improved in regard to the repeatability of measurements. A subsequently conducted repeatability study for a typical a-C:H based device allowed an estimate for the measurement error. The influence of the chopper frequency of the crystalline silicon calibration detector and a characteristic a-C:H based device was determined. A chopper frequency of 90 Hz was selected for actual measurements. In addition, the operation in the linear short-circuit current regime was verified. The quantum efficiency curves for three selected a-C:H based solar cell devices were acquired. It is evident from these quantum efficiency curves that a-C:H does contribute to the photogenerated current although the conversion of photons into electric current is not performed efficiently by the fabricated devices. It is recommended that future studies should address the cause of the high device resistance which appears to be not a simple bulk resistance of a-C:H.

Finally, there should be a comment on the prospect of using a-C:H for efficient solar cells. Up to this point, this research has shown basic photoconductive and photovoltaic behavior of a-C:H based devices. Nevertheless, at the present date, there is not enough information available on the intrinsic majority carrier type, the lifetime of carriers or the mobility of charge carriers in a-C:H. Also, the question of doping this material is still debated. This lack of information is partly due to the complicated nature of the a-C:H system. This system involves one more parameter than the related a-Si:H system. The additional parameter is the sp²/sp³ bonding ratio which is unique to carbon. One consequence of this additional parameter is the existence of two a-C:H films with the same bandgap, but different sp²/sp³ bonding ratio and different hydrogen content. For
these reasons the conclusion is reached that it is still too early to decide on the prospective use of a-C:H for photovoltaic devices.
6. References


[21] Smith, W., Nature, 7, 303 (1873)


Appendix: Microsoft Basic program listing

*** MAIN PROGRAM ***

'\$INCLUDE: 'graf.bi'
'\$INCLUDE: 'format.bi'
'\$INCLUDE: 'datim.bi'

DEFINT A-Z
DECLARE SUB Dlay (D!)
DECLARE SUB DeBounce ()
DECLARE FUNCTION WIFudge! (Wx!)
DECLARE SUB rs ()
DECLARE FUNCTION GETV! (Channel)
DECLARE SUB SetMono (WaveLenth$)
DECLARE FUNCTION VRatio! (NumSamples, SampleTime)
DECLARE SUB WISwp (Measurement$)
DECLARE SUB QRgraf (QRData!, Plt)
DECLARE SUB GSTR (X!, Y!, Q$, Ctr)
DECLARE FUNCTION JSC! (Qarray!, IrrFil$)
DECLARE FUNCTION ChkPot! (Samples)
DECLARE SUB SetZeroOff ()
DECLARE SUB PRNVGA (BSavFil$)
DECLARE SUB FindHome ()
DECLARE SUB FindWindow (p%)
DECLARE SUB FindMonoSet ()
DIM SHARED NoHome%, HomeCount%, NoDetente%, False%, True%
DIM SHARED WindowNo%, Filter1Pos%, Filter2Pos%, Filter3Pos%
DIM SHARED Filter1Wl%, Filter2Wl%, Filter3Wl%, Home%
DIM SHARED Auto%, Testing%, SingleStart$, Calibrating%

COMMON SHARED LastDirection AS INTEGER, NumCell AS INTEGER, Cell$
COMMON SHARED PulseCount AS DOUBLE
COMMON SHARED D2 AS INTEGER
COMMON SHARED Pper10N AS SINGLE
COMMON SHARED StartHL AS SINGLE
COMMON SHARED I1 AS INTEGER
COMMON SHARED I2 AS INTEGER
COMMON SHARED WL AS SINGLE, Wd1 AS SINGLE, Wd2 AS SINGLE
COMMON SHARED Wr1 AS SINGLE, Wr2 AS SINGLE
COMMON SHARED Start$, Menu$, ScrMode%
COMMON SHARED Blue&, Green&, Cyan&, Red&, Magenta&, Amber&, White&
COMMON SHARED Grey&,LtBlue&,LtGreen&,LtCyan&,LtRed&,LtMagenta&
COMMON SHARED YELLOW&, BrtWhite&, Black&, Blinking&

TYPE MeasureData 'LEN = 256
QDat(60) AS SINGLE
CalNum AS INTEGER
Info AS STRING * 10
END TYPE

TYPE QRindex
CellName AS STRING * 25
MRec(1 TO 4) AS LONG
END TYPE

DIM QVrCal(60) AS SINGLE
DIM qcal(60) AS SINGLE
DIM ZEROOFF(4, 12) AS SINGLE
DIM MD AS MeasureData
DIM QRndx AS QRindex
DIM Qsum(60) AS SINGLE
DIM SHARED IOAdrs, Port: IOAdrs = &H220: Port = 13'& New
DIM SHARED OpenedWindow1%, ClosedWindow1%, OpenedWindow2%

RESTORE MonoWaveCal
READ Wd1, Wd2, Wr1, Wr2
MonoWaveCal:
DATA 474.0, 828.2
DATA 467.1, 823.1

RESTORE ColorNumbers
READ Black&, Blue&, Green&, Cyan&, Red&, Magenta&, Amber&, White&
READ Grey&, LtBlue&, LtGreen&, LtCyan&, LtRed&, LtMagenta&
READ YELLOW&, BrtWhite&, Blinking&, ScrMode%
ColorNumbers:
DATA 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,0

VIDSET 'set video variables
VDISK$ = "d:\"

' File Names
IrrFil$ = "NAM1.5GL"
StandardQ$ = "ecdstd.q" ' 'Q data for standard cell
VRatioData$ = "vrncal.rat" ' 'Voltage ratios from calibration

False% = 0: True% = NOT False%
Home% = False%' Assume filter wheel not necessarily in home position
NoHome% = False%
NoDetente% = False%
Auto% = True%' Automatic mode (filter wheel etc.)
Testing% = False%' True%' Test software mode

' Positions on filter wheel
OpenedWindow1% = 1' First opened window
ClosedWindow1% = 2' First closed window
OpenedWindow2% = 3' Second opened window
Filter1Pos% = 5' Filter#1
Filter2pos% = 7' Filter#2
Filter3pos% = 9' Filter#3

Filter1Wl% = 640 'Wavelength at which to switch to filter #1
Filter2Wl% = 700 ' #2
Filter3Wl% = 800 ' #3

' Start at the following wavelengths to measure:
SingleStart$ = "350" ' All top cells, including singles
TandemBotStart$ = "350" ' bottom cell of tandem
TripleBotStart$ = "500" ' bottom cell of triple
CalibrateStart$ = "350" ' calibration of standard cell

' Return to the following wavelengths after measuring:
SingleRet$ = "550" ' single cell
TandemTopRet$ = "550" ' tandem top cell
TandemBotRet$ = "550" ' tandem bottom cell
TripleTopRet$ = "590" ' triple top cell
TripleMidRet$ = "720" ' triple middle cell
TripleBotRet$ = "550" ' triple bottom cell

IF Testing% THEN ' Used only for testing software
  Filter1Wl% = 440
  SingleRet$ = "420"
  TandemTopRet$ = "420"
  TandemBotRet$ = "420" ' tandem bottom cell
  TandemBotStart$ = "420"
  TripleTopRet$ = "420" ' triple top cell
  TripleMidRet$ = "420" ' triple middle cell
  TripleBotRet$ = "420" ' triple bottom cell
  TripleBotStart$ = "420"
  CalibrateStart$ = "420" ' calibration of standard cell
OUT IOAdrs + 9, 1 'Set gain to 2 (For -2.5V to +2.5V) [PCL-812PG]
OUT IOAdrs + 11, 1 'Enable software trigger [PCL-12PG]
OUT IOAdrs + 13, 7 'release mono clutch

StartWL = INT(ChkPot!(100) / 10 + .5) * 10' WL to nearest 10 nM
Pper10N = 666 + 2 / 3
PulseCount = 0
D2 = 1

OPEN "COM1:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #5
OPEN "COM2:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #6
PRINT #5, " "
PRINT #6, " "
PRINT #5, "G24"
PRINT #6, "G24"
CLOSE 5
CLOSE 6
RANGE1 = 1
RANGE2 = 1

' The following file contains the Q values of the Standard Cell
OPEN "c:\q\" + StandardQ$ FOR INPUT AS #1
FOR i = 0 TO 60
   INPUT #1, WL, qcal(i)
NEXT: CLOSE #1

' The following file contains the calibration data consisting of
' the ratios of the test voltages over the reference voltages
OPEN "c:\q\" + VRatioData$ FOR INPUT AS #1
FOR i = 0 TO 60
   INPUT #1, WL, QVrCal(i)
NEXT: CLOSE #1

'IF Auto% THEN FindHome
DO
ERASE Qsum, MD.QDat
OPEN "D:\SIGNAL. INT" FOR OUTPUT AS #4
WRITE #4, DATE$
WRITE #4, TIME$

*************** Menu ***************
CLS
COLOR LtBlue&, Black&
H = 29: V = 7
LOCATE V, H: PRINT "Q Measurement ----- 1"
LOCATE V + 2, H: PRINT "Set Monochrometer - 2"
LOCATE V + 4, H: PRINT "Check Calibration - 3"
LOCATE V + 6, H: PRINT "Calibrate --------- 4"
LOCATE V + 8, H: PRINT "Change Filter ----- 5"
LOCATE V + 10, H: PRINT "Quit -------------- Q"
Menu$ = UCASE$(INPUT$(1))
CLS
' ********************************************

IF Menu$ = "1" THEN '  ^^^^^^^^^ Q Measurement ^^^^^^^^^
   GOSUB Q
END IF

IF Menu$ = "2" THEN '  ^^^^ Set Monochrometer ^^^^^
   GOSUB SetM
END IF

IF Menu$ = "3" THEN '  ^^^^^ Check Calibration ^^^^^
   GOSUB CheckCalibration
END IF

IF Menu$ = "4" THEN '  ^^^^^ Calibrate ^^^^^
   GOSUB Calibrate
END IF

IF Menu$ = "5" THEN '  ^^^^^ Change Filter ^^^^^
   GOSUB ChangeFilter
END IF

IF Menu$ = "Q" THEN EXIT DO ' ^^^ Quit ^^^^^

CLOSE
LOOP ' Menu loop

'   %%% End Program Here %%%
CLS
LOCATE 10, 20: PRINT "Setting filter wheel to an open window";
IF Auto% THEN FindWindow (10)' Set filter wheel to an open window
CLS
LOCATE 10, 20: PRINT " Finished ";
OUT IOAdrs + 13, 7 'release mono clutch

END' ****** Program End ******

*** CALIBRATION SUBROUTINE ***

CalibQVr:
Calibrating% = True%
IF Auto% THEN
'  LOCATE 2, 1: PRINT "Finding window "; ClosedWindow1%
   FindWindow (ClosedWindow1%)
ELSE
   COLOR Cyan&, Blue&: PUWINDO 5, 20, 7, 40
   LOCATE 7, 28: PRINT "Setup for Q Calibration";
   LOCATE 9, 32: PRINT "Any Key to Start";
   Q$ = INPUT$(1)
   LOCATE 7, 28: PRINT " Uncover Source ";
END IF
CALL SetZeroOff: ' Q$ = INPUT$(1)
IF Auto% THEN
'  LOCATE 2, 1: PRINT "Finding window "; OpenedWindow2%
   FindWindow (OpenedWindow2%)
ELSE
   Q$ = INPUT$(1)
   PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
END IF
Start$ = CalibrateStart$
WISwp "QVrCal"
Calibrating% = False%
IF NOT (Testing%) THEN
OPEN "C:\q\" + VRatioData$ FOR OUTPUT AS #1
FOR i = 0 TO 60
   PRINT #1, USING "###  .######", 350 + i * 10; QVrCal(i)
NEXT: CLOSE #1
END IF
CLOSE #3
RETURN
*** QUANTUM EFFICIENCY MEASUREMENT SUBROUTINE ***

Q: 'Q Measurement Subroutine
'GOTO test
OPEN "D:\DAT.OUT" FOR OUTPUT AS #2
SCREEN 0, 0, 0
ScrMode% = 0
IF Auto% AND NOT (Home%) THEN FindHome'  Find home position on filter wheel
COLOR Cyan&, Blue&: PUWINDO 5, 10, 7, 60
LOCATE 7, 22: PRINT "Single, Tandem, Triple or Main Menu";
LOCATE 9, 29: PRINT "Enter 1, 2, 3 or Return";
NumCell = VAL(INPUT$(1))
PUWINDO 0, 0, 0, 0
IF NumCell = 0 THEN
GOT0 EndQ'  Goto end of program
COLOR Cyan&, Blue&: PUWINDO 5, 10, 7, 60
LOCATE 9, 13: PRINT "Enter Cell Name: ";
QRndx.CellName = VALIN$(25, "")
PUWINDO 0, 0, 0, 0

** Top Cell or Single Cell Q **
IF NOT (Auto%) OR NumCell > 1 THEN
COLOR Cyan&, Blue&: PUWINDO 5, 20, 7, 40
LOCATE 7, 30
END IF
SELECT CASE NumCell
CASE 1: 'Single cell
IF NOT (Auto%) THEN
PRINT "Cover Source";
END IF
Return1$ = SingleRet$
CASE 2: PRINT "Setup for Top Cell Q";
Return1$ = TandemTopRet$
Return2$ = TandemBotRet$
Cell2Start$ = TandemBotStart$
Cell$ = "Top"
CASE 3: PRINT "Setup for Top Cell Q";
Return1$ = TripleTopRet$
Return2$ = TripleMidRet$
Return3$ = TripleBotRet$
Cell2Start$ = SingleStart$
Cell3Start$ = TripleBotStart$
Cell$ = "Top"
END SELECT
IF NOT (Auto%) OR NumCell > 1 THEN
    LOCATE 9, 32: PRINT "Any Key to Start";
    Q$ = INPUT$(1)
    PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
END IF
COLOR LtBlue&, Black&
IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window #"; ClosedWindow1%
    FindWindow (ClosedWindow1%)
    LOCATE 2, 1: PRINT " ";
ELSE
    LOCATE 7, 30: PRINT " Uncover Source ";
END IF

CALL SetZeroOff: ' Q$ = INPUT$(1)
COLOR LtBlue&, Black&
IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window #";OpenedWindow2%
    FindWindow (OpenedWindow2%)
ELSE
    Q$ = INPUT$(1)
    PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
END IF
Start$ = SingleStart$' First Cell Starting Point
ERASE MD.QDat
WISwp "Q" ' Do Top Cell Q
LOCATE 2, 1: PRINT " Hit RETURN to display graph and return to ";
PRINT Return1$; " ";
Q$ = INPUT$(1): QRgraf MD.QDat(), 1

    ** Tandem Cell Bottom or Triple Cell Middle Q **
SetMono Return1$
OUT IOAdrs + 13, 7 'release mono clutch
LOCATE 1, 1: PRINT " ";
BEEP
IF NumCell = 2 THEN
    PRINT " Hit RETURN to measure bottom cell ";
    Cell$ = "Bottom"
END IF
IF NumCell = 3 THEN
    PRINT " Hit RETURN to measure middle cell ";
    Cell$ = "Middle"
END IF
Q$ = INPUT$(1)
SCREEN 0, 0, 0
ScrMode% = 0
FOR i = 0 TO 60: Qsum(i) = Qsum(i) + MD.QDat(i): NEXT

SELECT CASE NumCell
CASE 2, 3
  IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window "; OpenedWindow1%
    FindWindow (OpenedWindow1%)
  END IF
  COLOR Cyan&, Blue&: PUWINDO 5, 20, 7, 40
  LOCATE 7, 28: PRINT "Setup for "; Cell$; " Cell Q";
  LOCATE 9, 32: PRINT "Any Key to Start";
  Q$ = INPUT$(1)
  PUWINDO 0, 0, 0, 0
  IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window "; ClosedWindow1%
    FindWindow (ClosedWindow1%)
  END IF
  IF NOT (Auto%) THEN LOCATE 7, 28: PRINT " Uncover Source "
  COLOR Blue&, Black&
  CALL SetZeroOff: ' Q$ = INPUT$(1)
  IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window "; OpenedWindow2%
    FindWindow (OpenedWindow2%)
  ELSE
    q$ = INPUT$(1)
    PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
  END IF
  Start$ = Cell2Start$ 2nd Cell Starting Point
  ERASE MD.QDat
  WISwp "Q"
  LOCATE 2, 1: PRINT " Hit RETURN to display ";
  IF NumCell = 2 THEN PRINT "Top & Bottom cell Q graphs ";
  IF NumCell = 3 THEN PRINT "graph and return to "; PRINT Return2$; " ";
  Q$ = INPUT$(1): QRgraf MD.QDat(), -2

  IF NumCell = 3 THEN ' Get mono ready for bottom cell of triple
    SetMono Return2$
    OUT IOAdrs + 13, 7 'release mono clutch
    BEEP
  END IF
  LOCATE 1, 1
IF NumCell = 2 THEN
  PRINT "Hit RETURN to display Sum and set mono to "; Return2$
END IF
IF NumCell = 3 THEN PRINT " Hit RETURN to measure bottom cell ";
  QS = INPUT$(1)
LOCATE 1, 1: PRINT "
SCREEN 0, 0, 0
ScrMode% = 0
FOR i = 0 TO 60: Qsum(i) = Qsum(i) + MD. QDat(i): NEXT
IF NumCell = 2 THEN
  QRgraf Qsum(), -4
  SetMono Return2$
  OUT IOAdrs + 13, 7 'release mono clutch
  LOCATE 1, 1: PRINT "
  BEEP
  QS = INPUT$(1)
END IF
END SELECT

** Triple Bottom Cell Q **
SELECT CASE NumCell
CASE 3
  Cell$ = "Bottom"
  IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window "; OpenedWindow1%
    FindWindow (OpenedWindow1%)
  END IF
  COLOR Cyan&, Blue&: PUWINDO 5, 20, 7, 40
  LOCATE 7, 28: PRINT "Setup for Bottom Cell Q";
  LOCATE 9, 32: PRINT "Any Key to Start";
  QS = INPUT$(1)
  PUWINDO 0, 0, 0, 0
  IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window "; ClosedWindow1%
    FindWindow (ClosedWindow1%)
  END IF
  IF NOT (Auto%) THEN LOCATE 7, 28: PRINT " Uncover Source ";
  CALL SetZeroOff: ' QS = INPUT$(1)
  IF Auto% THEN
    COLOR Blue&, Black&
    LOCATE 2, 1: PRINT "Finding window "; OpenedWindow2%
    FindWindow (OpenedWindow2%)
  ELSE
    QS = INPUT$(1)
PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
END IF
Start$ = Cell3Start$' 3rd Cell Starting Point
ERASE MD.QDat
WiSwp "Q"
LOCATE 2, 1: PRINT " Hit RETURN to display ";
PRINT "Top Middle & Bottom cell Q graphs ";
Q$ = INPUT$(1): QRgraf MD.QDat(), -3
LOCATE 1, 1
PRINT "Hit RETURN to display Sum and set mono to "; Return3$;
Q$ = INPUT$(1)
LOCATE 1, 1: PRINT 
SCREEN 0, 0, 0
ScrMode% = 0
FOR i = 0 TO 60: Qsum(i) = Qsum(i) + MD.QDat(i): NEXT
QRgraf Qsum(), -4
SetMono Return3$
OUT IOAdrs + 13, 7 'release mono clutch
LOCATE 1, 1: PRINT "
BEEP
Q$ = INPUT$(1)
END SELECT
CLOSE #2
T$ = TIME$
Hr = VAL(T$)
SCREEN 0, 0, 0
ScrMode% = 0
COLOR LtBlue&, Black&
LOCATE 1, 1: PRINT "Enter comments if any - ";
LOCATE 2, 1: PRINT 
LOCATE 2, 1: LINE INPUT Comments$
LPRINT FormatD$(Now#, "mmmm d, yyyyy"); " ";
LPRINT FormatD$(Now#, "h:mm AM/PM"); " "; Comments$
test:
CLS
LOCATE 10, 10: PRINT "Enter a file name to store the Q data under,
LOCATE 11, 10: PRINT "or just hit enter to continue."
LOCATE 13, 10: PRINT "File Name :"; : INPUT FileName$
IF FileName$ <> "" THEN
   SHELL ("copy d:\dat.out c:\q\qdata\" + FileName$)
   SHELL ("copy d:\qt.plt c:\newqdata\ov\curve\" + FileName$)
   SHELL ("pause")
   SHELL ("copy d:\dat.out c:\newqdata\ov\data\" + FileName$)
*** CHECK CALIBRATION SUBROUTINE ***

CheckCalibration: ' Check Calibration Subroutine
OPEN "D:\DAT.OUT" FOR OUTPUT AS #2
IF Auto% AND NOT (Home%) THEN FindHome' Find home position on filter wheel

IF NOT (Auto%) THEN
    COLOR Cyan&, Blue&: PUWINDO 5, 20, 7, 40
    LOCATE 7, 26: PRINT "Setup for Calibration Check";
    LOCATE 9, 32: PRINT "Any Key to Start";
ELSE
    LOCATE 2, 1: PRINT "Finding window #"; ClosedWindow1%
    FindWindow (ClosedWindow1%)’ Cover source
    LOCATE 2, 1: PRINT " astonished "
END IF
IF NOT (Auto%) THEN
    Q$ = INPUT$(1)
    LOCATE 7, 26: PRINT " Uncover Source ";
END IF
CALL SetZeroOff
IF Auto% THEN
    LOCATE 2, 1: PRINT "Finding window #"; OpenedWindow2%
    FindWindow (OpenedWindow2%)’ Uncover Source
    LOCATE 2, 1: PRINT " astonished 
ELSE
    Q$ = INPUT$(1)
    PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
END IF
Start$ = CalibrateStart$
ERASE MD.QDat
WISwp "Q"
QRndx.CellName = "Calibrated Cell Q"
LOCATE 2, 1: PRINT " Hit RETURN to display stored graph ";
Q$ = INPUT$(1): QRgraf qcal(), 7
LOCATE 2, 1: PRINT "Hit RETURN to display graph ";
Q$ = INPUT$(1): QRgraf MD.QDat(), -2
LOCATE 2, 1: PRINT "Returning to "; SingleRet$; " nM 
SetMono SingleRet$
OUT IOAdrs + 13, 7 'release mono clutch
LOCATE 1, 1: PRINT "
LOCATE 2, 1: PRINT "
BEEP
Q$ = INPUT$(1)
SCREEN 0, 0, 0
ScrMode% = 0
CLOSE #2
RETURN

*** CALIBRATION SUBROUTINE ***

Calibrate: 'Calibrate Subroutine
IF Auto% AND NOT (Home%) THEN FindHome' Find home position on filter wheel
OPEN "D:\LAMP.INTM" FOR OUTPUT AS #3
WRITE #3, DATE$
WRITE #3, TIME$
GOSUB CalibQVr
LOCATE 2, 3: PRINT "Returning to "; SingleRet$; " nM "
SetMono SingleRet$
OUT IOAdrs + 13, 7 'release mono clutch
BEEP
LOCATE 2, 3: PRINT "Hit RETURN to continue "
Q$ = INPUT$(1)
CLS : LOCATE 10, 20: PRINT "Store Lamp data? (Y)/N";
Q$ = UCASE$(INPUT$(1))
IF Q$ <> "N" AND NOT (Testing%) THEN
    LOCATE 10, 20: PRINT "Printing lamp intensity data"
    LOCATE 15, 1: SHELL ("PRINT d:\lamp.int")
    LOCATE 10, 20: PRINT "Saving lamp intensity data"
    LOCATE 15, 1: SHELL ("copy d:\lamp.int c:\q\calib")
END IF
RETURN

*** SUBROUTINE FOR MONOCHROMATOR SETTING ***

SetM: 'Set Monochrometer Subroutine
FindMonoSet
LOCATE 3, 5: PRINT "Enter desired setting ";
    INPUT NEWwl$
    NEWwl! = VAL(NEWwl$)
LOCATE 3, 5: PRINT " 
LOCATE 14, 20: PRINT "Target setting "; NEWwl!
LOCATE 15, 20: PRINT " ": LOCATE 15, 40: PRINT " 
IF NEWwl! < 350 AND NEWwl$ <> "0" AND NEWwl$ <> "" THEN GOSUB 200
IF NEWwl! >= 350 AND NEWwl! <= 950 THEN SetMono (NEWwl$)
RETURN

*** SUBROUTINE FOR FILTER CHANGE ***

Changefilter:
IF NOT (Home%) THEN FindHome
DO
  V = 7: H% = 30
  LOCATE V, H: PRINT "Opened Window --- O"
  LOCATE V + 2, H%: PRINT "Closed Window --- C"
  LOCATE V + 4, H%: PRINT "Filter # 1 ------ 1"
  LOCATE V + 6, H%: PRINT "Filter # 2 ------ 2"
  LOCATE V + 8, H%: PRINT "Filter # 3 ------ 3"
  LOCATE V + 10, H%: PRINT "Home Position --- H"
  LOCATE V + 12, H%: PRINT "Main Menu -------- Esc"
  Filter$ = UCASE$(INPUT$(1))
  Temp% = Home%
  Home% = False%
  SELECT CASE Filter$
    CASE "O": F = OpenedWindow2%
    CASE "C": F = ClosedWindow1%
    CASE "1": F = Filter1Pos%
    CASE "2": F = Filter2pos%
    CASE "3": F = Filter3pos%
    CASE "H": CLS: FindHome
    CASE ELSE:
      Home% = Temp%
  END SELECT
  IF Filter$ <> "H" AND Filter$ <> CHR$(27) THEN FindWindow (F)
  LOOP UNTIL Filter$ = CHR$(27)
RETURN

*** SUBROUTINE FOR FILTER WHEEL ***

NearHome:
TIMER OFF
' 2 seconds have gone by since last detente. This means next
' detente should be home position
HomeCount% = HomeCount% + 1
IF HomeCount% > 1 THEN NoDetente% = True% ' No detentes found
RETURN

200 :
RETURN

*** MONOCHROMATOR WAVELENGTH DETERMINATION ***

FUNCTION ChkPot! (Samples)

OUT IOAdrs + 9, 0 'Set gain to 1 (For -5V to +5V) [PCL-812PG]
OUT IOAdrs + 11, 1 'Enable software trigger [PCL-12PG]
Ch = 2
OUT IOAdrs + 10, Ch 'select channel
Sum& = 0
FOR i = 1 TO Samples
  OUT IOAdrs + 12, 0 'trigger A/D conversion
  FOR J = 1 TO 20: k! = k! + J: NEXT J
  DO
    HI = INP(IOAdrs + 5)
    LOOP UNTIL HI < 16 'loop until conversion complete
    lo = INP(IOAdrs + 4)
  ' GetV1! = (HI * 256 + LO - 2048) / 4096 * 10 / 1
  Sum& = Sum& + HI * 256 + lo
NEXT i
 ' PRINT Sum& / Samples

Sum& = INT(10 * Sum& / Samples + .5) / 10
m1! = (650 - 350) / (3082.43 - 2314.91)
m2! = (950 - 650) / (3849.06 - 3082.43)
SELECT CASE Sum&
CASE IS <= 3082.43
  ChkPot! = 350 + m1! * (Sum& - 2314.91)
CASE IS > 3082.43
  ChkPot! = 650 + m2! * (Sum& - 3082.43)
END SELECT

END FUNCTION
*** SUBROUTINE 'DEBOUNCE' ***

SUB DeBounce
   Lasti% = INP(IOAdrs + 6)
   ConsecCount& = 1
   DO
      DO
         i% = INP(IOAdrs + 6)
         PRINT "down", ConsecCount&
         IF Lasti% = i% THEN ' Consecutive?
            ConsecCount& = ConsecCount& + 1
         ELSE
            PRINT ConsecCount&
            ConsecCount& = 0
            Lasti% = i%
         END IF
      LOOP UNTIL ConsecCount& = 300
   LOOP UNTIL (i% AND 3) > 0 ' Switch down?
   'PRINT ConsecCount&
END SUB

*** DELAY SUBROUTINE ***

SUB Dlay (D!)
   t1! = TIMER
   DO
      FOR i% = 1 TO 100: NEXT i%
      LOOP WHILE TIMER - t1! < D!
   END SUB

*** SUBROUTINE FOR FILTER WHEEL HOME POSITION ***

SUB FindHome
   NoHome% = False%
   WheelError% = False%
   HomeTime% = False%
   DetenteCount% = 0
   Home% = False%
LOCATE 10, 20: PRINT "Finding home position on filter wheel."

'Before looking for long home detente interval, verify that detente
'signal exists.
'Wheel is at rest. Check to see if it is on a detente. 
OUT IOAdrs + 13, 7' Stop motor at next detente (home position). 
b% = 3 AND INP(IOAdrs + 6)' Checking for detente signal. 
IF b% = 0 THEN Delay 1.5' If not on detent, allow to find next. 
b% = 3 AND INP(IOAdrs + 6)' Checking for detente signal. 
IF b% = 0 THEN ' If still not on detent wait 5 seconds. 
    (May be on long interval) 
    SLEEP 5 
b% = 3 AND INP(IOAdrs + 6)' Checking for detente signal. 
IF b% = 0 THEN WheelError% = True%' Problem 
END IF 

IF WheelError% = False% THEN ' Detente found. Look for home pos. 
OUT IOAdrs + 13, 15' Start motor. 
tl! = TIMER' Start time count between detentes. 
StartTime! = tl!' Start beginning time count. 
PRINT "here"; 
DO' Look for next detente 
b% = 3 AND INP(IOAdrs + 6) 
    TimeElapsed! = TIMER - tl! 
    LOOP UNTIL b% > 0 OR TimeElapsed! > 2 

'Detente found or approaching home detente 

tl! = TIMER 
TotalTime! = TIMER - StartTime! 
SOUND 900, .05 
Dlay .5' Wait for switch to leave detente 

IF b% > 0 THEN 
    DetenteCount% = DetenteCount% + 1 
    LOCATE 1, 1: PRINT USING "Detente Count = ##"; 
    DetenteCount% 
    LOCATE 2, 1: PRINT USING "Time between detentes = ##.##"; 
    TimeElapsed! 
    LOCATE 3, 1: PRINT USING "Total time = ##.##"; TotalTime! 
END IF 

IF TimeElapsed! > 2 THEN HomeTime% = True%' Home is next detente 

IF TotalTime! > 18 THEN NoHome% = True% 

LOOP UNTIL HomeTime% OR NoHome%
END IF

OUT IOAdrs + 13, 7'  Stop motor at next detente (home position).
WindowNo% = 1
CLS
LOCATE 10, 20
IF WheelError% THEN
  PRINT "There is a problem with the filter wheel."
  LOCATE 11, 20: PRINT "Check to see that it is resting on a detente."
  LOCATE 12, 20: PRINT "Hit ENTER when ready."
  INPUT a$
ELSEIF NoDetent% THEN
  PRINT "No detentes found on filter wheel."
  LOCATE 11, 20: PRINT "Cannot find home position."
ELSEIF NoHome% THEN
  PRINT "Detentes found, but cannot find home position."
ELSE
  'Don't return from sub until wheel arrives at home detente
  DO
    'Look for next detente
    b% = 3 AND INP(IOAdrs + 6)
    LOOP UNTIL b% > 0
    Home% = True%
    SOUND 700, .2
    Dlay .5'  Wait for switch to leave detente
END IF

'SOUND 800, .2
END SUB

*** SUBROUTINE TO FIND MONOCHROMATOR POSITION ***

SUB FindMonoSet
  OUT IOAdrs + 13, D2 * 4 + 1 * 2 + 1 'release mono clutch
  LastDirection = NOT (D2)' ^^New  (make setmono change dir.)
  DO
    SOUND 800, .6
    WLGuess! = INT((StartWL + PulseCount * 10 / Pper10N) * 100000 + .5) / 100000
    WLMeas = INT(ChkPot!(100) / 10 + .5) * 10'  WL to nearest 10 nM
    LOCATE 4, 5: PRINT "Hit RETURN if position is ";
    test = (WLMeas > WLGuess! + 5 OR WLMeas < WLGuess! - 5)
    IF test THEN ' WLGuess is off
      PRINT WLMeas;
  END IF
StartWL = WLMees
PulseCount = 0
D2 = 1
ELSE ' WLGues is close
PRINT WLGues!
END IF
LOCATE 3, 5: PRINT "Enter current monochrometer reading ":
INPUT Q$
LOCATE 3, 5: PRINT ";
LOCATE 4, 5: PRINT ";
LOOP UNTIL (VAL(Q$) >= WLMees - 10 AND VAL(Q$) <= WLMees + 10) OR Q$ = ""
IF Q$ <> "" THEN ' New WL given by user
   StartWL = VAL(Q$)
   PulseCount = 0
   D2 = 0
END IF
LastDirection = NOT (D2)
END SUB

*** SUBROUTINE TO FIND A FILTER WHEEL WINDOW ***

SUB FindWindow (p%)
COLOR Blue&, Black&
LOCATE 2, 1: PRINT SPC(50);
LOCATE 2, 1
PRINT "Finding": COLOR LtBlue&, Black&: PRINT p%;
COLOR Blue&, Black&
LOCATE 2, 13
PRINT "@ Window": COLOR LtBlue&, Black&: PRINT WindowNo%;

WindowInc% = p% - WindowNo%
IF p% < WindowNo% THEN
   WindowInc% = p% - WindowNo% + 10
END IF
SELECT CASE WindowInc%
CASE IS = 0
 'do nothing
CASE IS = 1
   OUT IOAdrs + 13, 15' Start motor
   Delay .5' Wait for switch to leave detente
CASE IS >= 2
   OUT IOAdrs + 13, 15' Start motor
Dlay .5' Wait for switch to leave detente

FOR i% = 1 TO WindowInc% - 1' Increment p%-1 detentes from home

DO
    b% = 3 AND INP(IOAdrs + 6)
LOOP UNTIL b% > 0 'OR NoDetent%

LOCATE 2, 22: PRINT FormatI$((WindowNo% + i%) MOD 10, "##")
SOUND 900, .05
Dlay .5' Wait for switch to leave detente
NEXT i%

END SELECT
WindowNo% = (WindowNo% + WindowInc%) MOD 10
OUT IOAdrs + 13, 7' Stop motor at next detente

DO' Suspend this subroutine until wheel stops
    b% = 3 AND INP(IOAdrs + 6)
LOOP UNTIL b% > 0 'OR NoDetent%
LOCATE 2, 22: PRINT FormatI$(WindowNo% MOD 10, "##")
SOUND 1000, .1
Dlay .3
LOCATE 2, 1: PRINT SPC(50);

END SUB

*** FUNCTION TO OBTAIN A VOLTAGE ***

FUNCTION GETV! (Ch)

    OUT IOAdrs + 10, Ch 'select channel
    OUT IOAdrs + 12, 0 'trigger A/D conversion
    FOR J = 1 TO 20: k! = k! + J: NEXT J
    DO
        HI = INP(IOAdrs + 5)
    LOOP UNTIL HI < 16 'loop until conversion complete
    lo = INP(IOAdrs + 4)
    GETV! = (HI * 256 + lo - 2048) / 4096 * 10 / 2

END FUNCTION

SUB GSTR (X!, Y!, Q$, Ctr)
DIM CA((4 + CHRy * INT((CHRx * LEN(Q$) + 7) / 8)) \ 2 - 1)
LOCATE 1, 1: PRINT Q$
GET (0, 0)-(CHRx * LEN(Q$) - 1, CHRy - 1), CA
SELECT CASE Ctr
   CASE 0: XP! = X!: YP! = Y! 'right of x
   CASE 1 'center about x
      XP! = X! - CHRx * LEN(Q$) \ 2: YP! = Y!
   CASE 2 'center about y left of x
      XP! = X! - CHRx * LEN(Q$): YP! = Y! - CHRy \ 2 + 1
END SELECT
PUT (XP!, YP!), CA
LOCATE 1, 1: PRINT STRING$(LEN(Q$), 32)
END SUB

*** FUNCTION TO CALCULATE THE SHORT-CIRCUIT CURRENT ***

FUNCTION JSC! (Q!(), IrrFil$)
   CONST Qel = 1.602E-19 'electron charge
   SHARED IrrFil$
   OPEN "T", #1, "c:\q\" + IrrFil$
   Jt! = 0
   FOR i = 0 TO 60
      INPUT #1, IrrWl!, Flux!
      Jt! = Jt! + 10! * Q!(i) * Flux!
   NEXT i
   CLOSE #1
   JSC! = Jt! * Qel * 1000000! 'uA/cm²
END FUNCTION

*** SUBROUTINE TO PLOT RESULTS ***

SUB QRgraf (a!(), G)
   SHARED IrrFil$, QRndx AS QRindex
   SCREEN GScrn
   ScrMode% = 11
   XI! = GMx / 9.5: YI! = GMy / 15
   IF G > 0 THEN
LINE (2 * XI!, 2.5 * YI!)-(8 * XI!, 2.5 * YI!)
LINE (2 * XI!, 12.5 * YI!)-(8 * XI!, 12.5 * YI!)
LINE (2 * XI!, 2.5 * YI!)-(2 * XI!, 12.5 * YI!)
LINE (8 * XI!, 2.5 * YI!)-(8 * XI!, 12.5 * YI!)
FOR i = 1 TO 19
  IF i MOD 2 = 1 THEN
    LINE (2 * XI!, (2.5 + i / 2) * YI!)-(2.05 * XI!, (2.5 + i / 2) * YI!)
    LINE (7.96 * XI!, (2.5 + i / 2) * YI!)-(8 * XI!, (2.5 + i / 2) * YI!)
  ELSE
    LINE (2 * XI!, (2.5 + i / 2) * YI!)-(2.1 * XI!, (2.5 + i / 2) * YI!)
    LINE (7.92 * XI!, (2.5 + i / 2) * YI!)-(8 * XI!, (2.5 + i / 2) * YI!)
    IF (i + 2) MOD 4 = 0 THEN
      GSTR 1.9 * XI!, (2.5 + i / 2) * YI!, FormatS$((20 - i) / 20, "#.#"), 2
    END IF
  END IF
END IF
NEXT
FOR i = 1 TO 59
  IF i MOD 5 = 0 THEN
    LINE ((2 + i / 10) * XI!, 12.5 * YI!)-((2 + i / 10) * XI!, 12.25 * YI!)
    LINE ((2 + i / 10) * XI!, 2.5 * YI!)-((2 + i / 10) * XI!, 2.75 * YI!)
    IF (i + 5) MOD 10 = 0 THEN
      GSTR (2 + i / 10) * XI!, 12.7 * YI!, LTRIM$(STR$(350 + i * 10)), 1
    END IF
  END ELSE
    LINE ((2 + i / 10) * XI!, 12.5 * YI!)-((2 + i / 10) * XI!, 12.4 * YI!)
    LINE ((2 + i / 10) * XI!, 2.5 * YI!)-((2 + i / 10) * XI!, 2.6 * YI!)
  END IF
NEXT
SELECT CASE G
CASE 1, 2, 3, 7
  GRAFPRN 0, FIX(1.3 * XI!), FIX(7 * YI!), 2, 2, 0, "Q"
CASE 4
  GRAFPRN 1, FIX(1.2 * XI!), FIX(8.6 * YI!), 2, 2, 0, "R,Q"
CASE 5
  GRAFPRN 0, FIX(1.3 * XI!), FIX(7 * YI!), 2, 2, 0, "T"
END SELECT
GSTR 5 * XI!, 13.4 * YI!, "Wavelength (nm)", 1
GSTR 2.5 * XI!, 1.9 * YI!, QRndx.CellName, 0
GSTR 6 * XI!, 1.9 * YI!, FormatD$(Now#, "mmmrn d, yyyy"); 0
IF G < 5 OR G = 7 THEN
  GSTR 7.3 * XI!, 3.2 * YI!, IrrFil$, 1
  GSTR 7.3 * XI!, 3.5 * YI!, "--------", 1
END IF
ELSEIF G < 0 THEN
  .
BLOAD VDISKS$ + "QT.PLT"
END IF

VIEW (2 * XI!, 2.5 * YI!)-(8 * XI!, 12.5 * YI!)
WINDOW (0, 1)-(60, 0)
IF G = -4 THEN I1 = (VAL(SingleStart$) - 350) / 10
IF G = 7 THEN
    I1 = 0: I2 = 60
END IF
FOR i = I1 TO I2
    IF i > I1 THEN
        LINE (i - 1, a!(i - 1))-(i, a!(i))
    END IF
NEXT
VIEW: WINDOW

SELECT CASE ABS(G)
    CASE 1, 7
        GSTR 7.3 * XI!, 3.8 * YI!, FormatS$(JSC(a!(), ""), "#.###"), 1
    CASE 2
        GSTR 7.3 * XI!, 4.3 * YI!, FormatS$(JSC(a!(), ""), "#.###"), 1
    CASE 3
        GSTR 7.3 * XI!, 4.8 * YI!, FormatS$(JSC(a!(), ""), "#.###"), 1
    CASE 4
        GSTR 7.3 * XI!, 5.1 * YI!, "-------", 1
        GSTR 7.3 * XI!, 5.4 * YI!, FormatS$(JSC(a!(), ""), "#.###"), 1
END SELECT

DEF SEG = GSeg: BS\SAVE VDISKS$ + "QT.PLT", 0, ScrnLen

END SUB

*** SET MONOCHROMATOR SUBROUTINE ***

SUB SetMono (NEWwl$)
    SHARED ScrMode%
    NEWwl! = VAL(NEWwl$)
    SELECT CASE NEWwl!
        CASE IS < 340: NEWwl! = 340' Limit lower bound to 340
        CASE IS > 960: NEWwl! = 960' Limit upper bound to 960
    END SELECT

    SELECT CASE RIGHT$(NEWwl$, 1)
CASE "s", "S": test = NEWwl!
NPulses& = INT(ABS(NEWwl!) + .5)
PulseCount = PulseCount + NPulses& * SGN(NEWwl!)

CASE ELSE
DeltaNEWwl! = NEWwl! - StartWL
ActualDeltawl! = PulseCount * 10 / Pper10N
DeltaPulses! = (DeltaNEWwl! - ActualDeltawl!) * Pper10N / 10
NPulses& = INT(ABS(DeltaPulses!) + .5)
PulseCount = PulseCount + NPulses& * SGN(DeltaPulses!)
test! = DeltaPulses!

END SELECT

SELECT CASE SGN(test!)
CASE 1: D2 = 1: Delay% = 18
CASE -1: D2 = 0: Delay% = 18
END SELECT
Extra% = 0
IF D2 <> LastDirection THEN ' Change direction
  ' Release, then engage clutch
  OUT IOAdrs + Port, 4 * D2 + 1 * 2 + 1'
  FOR J = 1 TO 2500: k! = k! + J: NEXT J
  OUT IOAdrs + Port, 4 * D2 + 0 * 2 + 1
  FOR J = 1 TO 2500: k! = k! + J: NEXT J
  Extra% = 0
END IF
LastDirection = D2
Port% = 13
Delay% = 36
'time1! = TIMER
BL = 4 * D2 + 2 * 0 + 0
BH = 4 * D2 + 2 * 0 + 1
OUT IOAdrs + 9, 0 'Set gain to 2
OUT IOAdrs + 10, 2 'Select channel
OUT IOAdrs + 11, 1 'Enable software trigger [PCL-12PG]
IF ScrMode% = 0 THEN COLOR YELLOW& + Blinking&, Black&
LOCATE 1, 10: PRINT "wl";
IF ScrMode% = 0 THEN COLOR LtBlue&, Black&
PRINT " = ";
LOCATE 6, 10
ml! = (650 - 350) / (3082.43 - 2314.91)
m2! = (950 - 650) / (3849.06 - 3082.43)
FOR i& = 1 TO NPulses& + Extra%
IF i& > 10 THEN Delay% = 31
OUT IOAdrs + 13, BL
    FOR J = 1 TO Delay%: k! = k! + J: NEXT J' set count to 31 in qhalo

OUT IOAdrs + 13, BH
IF (i& MOD 200) = 0 THEN ' Check potentiometer every 200 steps
    OUT IOAdrs + 12, 0  'trigger A/D conversion
    FOR J = 1 TO 300: NEXT J
    DO
        HI = INP(IOAdrs + 5)
    LOOP UNTIL HI < 16 'loop until conversion complete
lo = INP(IOAdrs + 4)
Sum& = HI * 256 + lo
SELECT CASE Sum&
CASE IS <= 3082.43
    Pot! = 350 + m1! * (Sum& - 2314.91)
CASE IS > 3082.43
    Pot! = 650 + m2! * (Sum& - 3082.43)
END SELECT

LOCATE 1, 15: PRINT USING "###"; Pot!; : PRINT " "
ELSE
    FOR J = 1 TO Delay%: k! = k! + J: NEXT J' set count to 31 in qhalo
END IF
NEXT i&
'LOCATE 2, 1: PRINT USING "###.##"; TIMER - time1!
IF ScrMode% = 0 THEN COLOR Blue&, Black&
LOCATE 1, 10: PRINT "wl = "; : PRINT USING "###.##"; ChkPot!(100); : PRINT " 
"

END SUB

*** SUBROUTINE FOR VOLTAGE OFFSET DETERMINATION ***

SUB SetZeroOff

    SHARED ZEROOFF() AS SINGLE, RANGE1, RANGE2

    COLOR Cyan&, Blue&: PUWINDO 3, 7, 20, 67
    LOCATE 4, 30: PRINT "Set Voltage Offsets";
    OUT IOAdrs + 9, 1 'Set gain to 2 (For -2.5V to +2.5V) [PCL-812PG]
    SLEEP 10
OPEN "COM1:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #5
OPEN "COM2:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #6
PRINT #5, " "
PRINT #6, " "
PRINT #5, "G24"
PRINT #6, "G24"

DO
S3! = 0: S1! = 0
FOR I1 = 1 TO 500
S3! = S3! + GETV(3)
S1! = S1! + GETV(4)
NEXT
S3! = S3! / 500: S1! = S1! / 500

IF ABS(S3!) > .2 OR ABS(S1!) > .2 THEN
    OUT IOAdrs + 13, 7
    SLEEP 2
    COLOR Blue&, Black&: PUWINDO 3, 7, 20, 67
    CLS
    FindHome
    FindWindow (ClosedWindow1%)
    CLS
    COLOR Cyan&, Blue&: PUWINDO 3, 7, 20, 67
    LOCATE 4, 30: PRINT "Set Voltage Offsets";
END IF
SLEEP 10
LOOP UNTIL ABS(S3!) < .2 AND ABS(S1!) < .2

PRINT #5, "G13"
PRINT #6, "G13"
S3! = GETV(3)
S1! = GETV(4)
IF S1! > 2.3 OR S3! > 2.3 THEN
    PRINT #5, "G24"
    PRINT #6, "G24"
    PRINT "FILTER WHEEL FAILED"
END
END IF

SLEEP 15
PRINT #5, "K21"
PRINT #6, "K21"
SLEEP 2
PRINT #5, "G24"
PRINT #6, "G24"
SLEEP 2

I2 = 1

DO
COUNT = 0

DO
S3OLD! = S3!: S1OLD! = S1!
S3! = 0: S1! = 0
FOR I1 = 1 TO 500
S3! = S3! + GETV(3)
S1! = S1! + GETV(4)
NEXT
S3! = S3! / 500: S1! = S1! / 500
COUNT = COUNT + 1
IF COUNT > 15 THEN EXIT DO
LOOP UNTIL COUNT > 10 AND ABS(S3OLD! - S3!) < .001 AND ABS(S1OLD! - S1!) < .001
ZEROOFF(3, I2) = S3!: ZEROOFF(4, I2) = S1!

IF I2 = 1 THEN
LOCATE 6, 11: PRINT USING "REF 500 mV=#.#####"; ZEROOFF(3, I2);
LOCATE 6, 40: PRINT USING "TEST 500 mV=#.#####"; ZEROOFF(4, I2);
PRINT #5, "G23"
PRINT #6, "G23"
END IF

IF I2 = 2 THEN
LOCATE 7, 11: PRINT USING "REF 200 mV=#.#####"; ZEROOFF(3, I2);
LOCATE 7, 40: PRINT USING "TEST 200 mV=#.#####"; ZEROOFF(4, I2);
PRINT #5, "G22"
PRINT #6, "G22"
END IF

IF I2 = 3 THEN
LOCATE 8, 11: PRINT USING "REF 100 mV=#.#####"; ZEROOFF(3, I2);
LOCATE 8, 40: PRINT USING "TEST 100 mV=#.#####"; ZEROOFF(4, I2);
PRINT #5, "G21"
PRINT #6, "G21"
END IF
IF I2 = 4 THEN
   LOCATE 9, 11: PRINT USING "REF 50 mV=#.#####"; ZEROOFF(3, I2);
   LOCATE 9, 40: PRINT USING "TEST 50 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G20"
   PRINT #6, "G20"
END IF

IF I2 = 5 THEN
   LOCATE 10, 11: PRINT USING "REF 20 mV=#.#####"; ZEROOFF(3, I2);
   LOCATE 10, 40: PRINT USING "TEST 20 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G19"
   PRINT #6, "G19"
END IF

IF I2 = 6 THEN
   LOCATE 11, 11: PRINT USING "REF 10 mV=#.#####"; ZEROOFF(3, I2);
   LOCATE 11, 40: PRINT USING "TEST 10 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G18"
   PRINT #6, "G18"
END IF

IF I2 = 7 THEN
   LOCATE 12, 11: PRINT USING "REF 5 mV=#.#####"; ZEROOFF(3, I2);  
   LOCATE 12, 40: PRINT USING "TEST 5 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G17"
   PRINT #6, "G17"
END IF

IF I2 = 8 THEN
   LOCATE 13, 11: PRINT USING "REF 2 mV=#.#####"; ZEROOFF(3, I2);
   LOCATE 13, 40: PRINT USING "TEST 2 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G16"
   PRINT #6, "G16"
END IF

IF I2 = 9 THEN
   LOCATE 14, 11: PRINT USING "REF 1 mV=#.#####"; ZEROOFF(3, I2);  
   LOCATE 14, 40: PRINT USING "TEST 1 mV=#.#####"; ZEROOFF(4, I2);
   PRINT #5, "G15"
   PRINT #6, "G15"
END IF

IF I2 = 10 THEN
   LOCATE 15, 11: PRINT USING "REF 500 uV=#.#####"; ZEROOFF(3, I2);
LOCATE 15, 40: PRINT USING "TEST 500 uV=#.#####"; ZEROOFF(4, I2);
PRINT #5, "G14"
PRINT #6, "G14"
END IF

IF I2 = 11 THEN
LOCATE 16, 11: PRINT USING "REF 200 uV=#.#####"; ZEROOFF(3, I2);
LOCATE 16, 40: PRINT USING "TEST 200 uV=#.#####"; ZEROOFF(4, I2);
PRINT #5, "G13"
PRINT #6, "G13"
END IF

IF I2 = 12 THEN
LOCATE 17, 11: PRINT USING "REF 100 uV=#.#####"; ZEROOFF(3, I2);
LOCATE 17, 40: PRINT USING "TEST 100 uV=#.#####"; ZEROOFF(4, I2);
END IF

I2 = I2 + 1
LOOP UNTIL I2 = 13

PRINT #5, "G24"
PRINT #6, "G24"

CLOSE 5
CLOSE 6

RANGE1 = 1
RANGE2 = 1

SLEEP 1
PUWINDO 0, 0, 0, 0:
SOUND 1000, .5

END SUB

*** SUBROUTINE FOR FILTER WHEEL TESTING ***

SUB testwheel
CLS
LOCATE 1, 1
   Up% = 6
   Lasti% = INP(&H220 + 6)
   OUT &H220 + 13, 15'   Start motor.
COUNT& = 0
DO
  i% = INP(&H220 + 6)
  IF i% <> Lasti% THEN
    PRINT Lasti%, COUNT&
    Lasti% = i%
    COUNT& = 0
  ELSE
    COUNT& = COUNT& + 1
  END IF
LOOP WHILE INKEY$ = ""
OUT &H220 + 13, 7' Stop motor.

END SUB

*** FUNCTION FOR THE TEST CELL AND CAL. DET. VOLTAGE RATIO ***

FUNCTION VRatio! (NS, st)

  SHARED ZEROOFF() AS SINGLE, V1SUM!, V3SUM!, RANGE1, RANGE2

  OUT IOAdrs + 9, 1 'Set gain to 2 (For -2.5V to +2.5V) [PCL-812PG]

  OPEN "COM1:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #5
  OPEN "COM2:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #6
  PRINT #5, " "
  PRINT #6, " "

  COUNT = 0

  DO
    V1OLD! = V1SUM!: V3OLD! = V3SUM!
    V1SUM! = 0: V3SUM! = 0

    FOR i = 1 TO NS
      'sum voltage ratios
      V1SUM! = V1SUM! + GETV(4)
      V3SUM! = V3SUM! + GETV(3)
      'delay ST *.05 sec between measurements
      IF st > 0 THEN st! = TIMER: WHILE TIMER - st! < st * .05: WEND
    NEXT

    V1SUM! = V1SUM! / NS - ZEROOFF(4, RANGE2)
V3SUM! = V3SUM! / NS - ZEROOFF(3, RANGE1)

COUNT = COUNT + 1

IF V3SUM! < .35 * 2.5 THEN RANGE1 = RANGE1 + 1: FLAG1 = 1
IF V3SUM! > .9 * 2.5 THEN RANGE1 = RANGE1 - 1: FLAG1 = 1
IF V1SUM! < .35 * 2.5 THEN RANGE2 = RANGE2 + 1: FLAG2 = 1
IF V1SUM! > .9 * 2.5 THEN RANGE2 = RANGE2 - 1: FLAG2 = 1

IF RANGE1 = 1 AND FLAG1 = 1 THEN PRINT #5, "G24"
IF RANGE1 = 2 AND FLAG1 = 1 THEN PRINT #5, "G23"
IF RANGE1 = 3 AND FLAG1 = 1 THEN PRINT #5, "G22"
IF RANGE1 = 4 AND FLAG1 = 1 THEN PRINT #5, "G21"
IF RANGE1 = 5 AND FLAG1 = 1 THEN PRINT #5, "G20"
IF RANGE1 = 6 AND FLAG1 = 1 THEN PRINT #5, "G19"
IF RANGE1 = 7 AND FLAG1 = 1 THEN PRINT #5, "G18"
IF RANGE1 = 8 AND FLAG1 = 1 THEN PRINT #5, "G17"
IF RANGE1 = 9 AND FLAG1 = 1 THEN PRINT #5, "G16"
IF RANGE1 = 10 AND FLAG1 = 1 THEN PRINT #5, "G15"
IF RANGE1 = 11 AND FLAG1 = 1 THEN PRINT #5, "G14"
IF RANGE1 = 12 AND FLAG1 = 1 THEN PRINT #5, "G13"

IF RANGE2 = 1 AND FLAG2 = 1 THEN PRINT #6, "G24"
IF RANGE2 = 2 AND FLAG2 = 1 THEN PRINT #6, "G23"
IF RANGE2 = 3 AND FLAG2 = 1 THEN PRINT #6, "G22"
IF RANGE2 = 4 AND FLAG2 = 1 THEN PRINT #6, "G21"
IF RANGE2 = 5 AND FLAG2 = 1 THEN PRINT #6, "G20"
IF RANGE2 = 6 AND FLAG2 = 1 THEN PRINT #6, "G19"
IF RANGE2 = 7 AND FLAG2 = 1 THEN PRINT #6, "G18"
IF RANGE2 = 8 AND FLAG2 = 1 THEN PRINT #6, "G17"
IF RANGE2 = 9 AND FLAG2 = 1 THEN PRINT #6, "G16"
IF RANGE2 = 10 AND FLAG2 = 1 THEN PRINT #6, "G15"
IF RANGE2 = 11 AND FLAG2 = 1 THEN PRINT #6, "G14"
IF RANGE2 = 12 AND FLAG2 = 1 THEN PRINT #6, "G13"

IF RANGE1 = 0 THEN RANGE1 = 1: FLAG1 = 0
IF RANGE1 = 13 THEN RANGE1 = 12: FLAG1 = 0
IF RANGE2 = 0 THEN RANGE2 = 1: FLAG2 = 0
IF RANGE2 = 13 THEN RANGE2 = 12: FLAG2 = 0

IF FLAG1 = 1 OR FLAG2 = 1 THEN COUNT = 0
IF FLAG1 = 1 OR FLAG2 = 1 THEN SLEEP 6
FLAG1 = 0
FLAG2 = 0
IF COUNT > 15 THEN EXIT DO
LOOP UNTIL COUNT > 10 AND ABS(V1OLD! - V1SUM!) < .001 AND
ABS(V3OLD! - V3SUM!) < .001

CLOSE 5
CLOSE 6

IF RANGE1 = 1 THEN V3SUM! = (V3SUM! / 10) * 500
IF RANGE1 = 2 THEN V3SUM! = (V3SUM! / 10) * 200
IF RANGE1 = 3 THEN V3SUM! = (V3SUM! / 10) * 100
IF RANGE1 = 4 THEN V3SUM! = (V3SUM! / 10) * 50
IF RANGE1 = 5 THEN V3SUM! = (V3SUM! / 10) * 20
IF RANGE1 = 6 THEN V3SUM! = (V3SUM! / 10) * 10
IF RANGE1 = 7 THEN V3SUM! = (V3SUM! / 10) * 5
IF RANGE1 = 8 THEN V3SUM! = (V3SUM! / 10) * 2
IF RANGE1 = 9 THEN V3SUM! = (V3SUM! / 10) * 1
IF RANGE1 = 10 THEN V3SUM! = (V3SUM! / 10) * .5
IF RANGE1 = 11 THEN V3SUM! = (V3SUM! / 10) * .2
IF RANGE1 = 12 THEN V3SUM! = (V3SUM! / 10) * .1

IF RANGE2 = 1 THEN V1SUM! = (V1SUM! / 10) * 500
IF RANGE2 = 2 THEN V1SUM! = (V1SUM! / 10) * 200
IF RANGE2 = 3 THEN V1SUM! = (V1SUM! / 10) * 100
IF RANGE2 = 4 THEN V1SUM! = (V1SUM! / 10) * 50
IF RANGE2 = 5 THEN V1SUM! = (V1SUM! / 10) * 20
IF RANGE2 = 6 THEN V1SUM! = (V1SUM! / 10) * 10
IF RANGE2 = 7 THEN V1SUM! = (V1SUM! / 10) * 5
IF RANGE2 = 8 THEN V1SUM! = (V1SUM! / 10) * 2
IF RANGE2 = 9 THEN V1SUM! = (V1SUM! / 10) * 1
IF RANGE2 = 10 THEN V1SUM! = (V1SUM! / 10) * .5
IF RANGE2 = 11 THEN V1SUM! = (V1SUM! / 10) * .2
IF RANGE2 = 12 THEN V1SUM! = (V1SUM! / 10) * .1

Vtemp! = V1SUM! / V3SUM!

COLOR LtBlue&
LOCATE 15, 73
PRINT USING "##.###"; V1SUM!
LOCATE 16, 73
PRINT USING "##.###"; V3SUM!
LOCATE 17, 73
PRINT USING "##.###"; Vtemp!
PRINT #4, USING "###.###  "; V3SUM!; V1SUM!; WL; Vtemp!
IF Calibrating% THEN
    PRINT #3, USING "###.###"; V3SUM!; V1SUM!; WL; Vtemp!
END IF
VRatio! = Vtemp!

END FUNCTION

*** FUNCTION FOR THE CORRECTION OF THE WAVELENGTH SETTING ***

FUNCTION WlFudge! (Wx!)
    WlFudge! = (Wd2 - Wd1) / (Wr2 - Wr1) * (Wx! - Wr1) + Wd1
END FUNCTION

*** SUBROUTINE FOR WAVELENGTH SCANNING ***

SUB WlSwp (m$)
    SHARED QVrCal() AS SINGLE, qcal() AS SINGLE, MD AS MeasureData,
    RANGE1, RANGE2
    SHARED IrrFil$, QRndx AS QRindex
    SHARED V3SUM!, V1SUM!
    StartingWL = VAL(Start$)' Starting Wavelength
    COLOR LtBlue&. Black&

    CLS
    SLEEP 1
    '11 = 7
    I1 = (StartingWL - 350) / 10
    I2 = I1 - 1
    SweepNum% = -1

    FOR i = I1 TO 60
        SweepNum% = SweepNum% + 1
        WL = 350 + i * 10'\^\^ New
        SELECT CASE WL
            CASE Filter1Wl%
                IF NOT (Auto%) THEN
                    COLOR Cyan&, Blue&: PUWINDO 8, 30, 7, 26
                    LOCATE 12, 35: PRINT "ALT-F TO RESUME";
                    COLOR 31, 0: LOCATE 10, 35: BEEP: PRINT "CHANGE FILTER";
                    DO: LOOP UNTIL INKEY$ = CHRS$(0) + CHRS$(33)
PUWINDO 0, 0, 0, 0: COLOR Blue&, Black&
ELSE
    LOCATE 2, 1: PRINT "Changing to filter #1 ";
    FindWindow (Filter1Pos%)
    LOCATE 2, 1: PRINT " ";
END IF
SLEEP 2
CASE Filter2Wl%
    FindWindow (Filter2pos%)
    SLEEP 2
CASE Filter3Wl%
    FindWindow (Filter3pos%)
    SLEEP 2
END SELECT
SELECT CASE WL
    CASE 830: WL = 834
END SELECT
SELECT CASE WL
    CASE 880: WL = 878
END SELECT
SELECT CASE WL
    CASE 890: WL = 894
END SELECT
SELECT CASE WL
    CASE 900: WL = 904
END SELECT
SELECT CASE WL
    CASE 910: WL = 914
END SELECT
SELECT CASE WL
    CASE 920: WL = 925
END SELECT

'\^ New
IF i = 11 THEN
    LastDirection = NOT (D2)
ELSE
    SOUND 1000, 1
    SetMono STR$(WlFudge!(WL))
END IF

DO
    wlRead! = ChkPot!(100): wlErr = ABS(WlFudge!(WL) - wlRead!)
    LOCATE 1, 10: PRINT "wl = ";
    PRINT USING "###.#"; wlRead!
    IF wlErr > 2 THEN
        FindMonoSet
        SetMono STR$(WlFudge!(WL))
        wlRead! = ChkPot!(100): wlErr = ABS(WlFudge!(WL) - wlRead!)
        LOCATE 1, 10: PRINT "wl = "; PRINT USING "###.#"; wlRead!; PRINT ""
    END IF
LOOP WHILE wlErr > 2

SLEEP 2

VR! = VRatio(500, 0)

VtrRatio! = VR!
    ' Qt=(Test/Reference)*(Reference/Standard)*Qs  {Q of test cell}
    '    VR!=Test/Reference
    '    QVrCal(i)=(Reference/Standard) {Calibrated voltage ratios}
    '    Qs=QCAL(i)  Q of standard cell
SELECT CASE WL
    CASE IS > 900
        TextColor% = Grey&
        CASE IS > 820
            TextColor% = Red&
            CASE IS > 620
                TextColor% = LtRed&
                CASE IS > 580
                    TextColor% = Amber&
                    CASE IS > 540
                        TextColor% = YELLOW&
                        CASE IS > 500
                            TextColor% = Green&
                            CASE IS > 460
                                TextColor% = Cyan&
                                CASE IS > 340
                                    TextColor% = Blue&
END SELECT
COLOR Blue&
IF SweepNum% = 0 THEN
IF m$ = "Q" THEN
LOCATE 20, 55
PRINT "Q = Vratio / Vrcal * Qs"
PRINT "Q = (T/R) / Vrcal * Qs"
END IF
LOCATE 15, 59
PRINT "Test =";
LOCATE 16, 59
PRINT "Reference =";
LOCATE 17, 58
PRINT "Ratio(T/R) =";
END IF

SELECT CASE m$
CASE "Q"
VR! = VR! / QVrCal(i) * qcal(i)' Q of test cell
IF VR! < 0 THEN VR! = 0
MD.QDat(i) = VR!
COLOR LtBlue&
LOCATE 21, 54
PRINT USING "#.##= #.## / ##.## * #.##"; VR!; VtrRatio!; QVrCal(i); qcal(i)
LOCATE 22, 54
PRINT USING "##.##"; VtrRatio! / QVrCal(i);
PRINT #2, USING "###, .#### ###"; WL; VR!
CASE "QVrCal"
QVrCal(i) = VR!
CASE "T"
VR! = VR! / QVrCal(i)
MD.QDat(i) = VR!
PRINT WL, qcal(i)
END SELECT
IF SweepNum% = 0 THEN
LOCATE 5, 1
IF m$ = "Q" AND NumCell > 1 THEN
PRINT Cell$; " cell "; m$; " of";
IF NumCell = 2 THEN PRINT " (tandem) ";
IF NumCell = 3 THEN PRINT " (triple) ";
PRINT QRndx.CellName;
ELSE
PRINT m$; " of (single) ";
PRINT QRndx.CellName;
END IF
END IF
LOCATE (SweepNum% MOD 18) + 6, (SweepNum% \ 18) * 15 + 3
COLOR TextColor%: PRINT USING "### = #.#####"; WL; VR!
' PRINT #2, USING "###, #.###"; WL; VR!
I2 = I2 + 1
Altend% = a$ = CHR$(1)
Tailing% = WL >= 710' Wavelength greater than this
Tailing% = Tailing% AND NOT (Testing%) AND NOT (Calibrating%)
IF Altend% OR Tailing% THEN
  FOR J = i + 1 TO 60: MD.QDat(J) = 0!: NEXT: EXIT FOR
END IF
NEXT

OPEN "COM1:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #5
OPEN "COM2:2400,N,8,1,CS,DS,CD" FOR RANDOM AS #6
PRINT #5, "    "
PRINT #6, "    "
PRINT #5, "G24"
PRINT #6, "G24"
CLOSE 5
CLOSE 6

RANGE1 = 1
RANGE2 = 1

SLEEP 1
COLOR LtBlue&, Black&
LOCATE 1, 1: PRINT SPC(40);
LOCATE 5, 65: PRINT SPC(15);
FOR i% = 13 TO 23' Erase extraneous stuff from screen
  LOCATE i%, 48: PRINT SPC(32);
NEXT i%
BEEP

END SUB