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Quantum efficiency characterization of back-illuminated CCDs Part 2: reflectivity measurements

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ABSTRACT

The usual quantum efficiency (QE) measurement heavily relies on a calibrated photodiode (PD) and the knowledge of the CCD's gain. Either can introduce significant systematic errors. But reflectivity can also be used to verify QE measurements. $1 - R \geq \mathrm{QE}$, where R is the reflectivity, and over a significant wavelength range, $1 - R = \mathrm{QE}$. An unconventional reflectometer has been developed to make this measurement. R is measured in two steps, using light from the lateral monochromator port via an optical fiber. The beam intensity is measured directly with a PD, then both the PD and CCD are moved so that the optical path length is unchanged and the light reflects once from the CCD; the PD current ratio gives R. Unlike traditional schemes this approach makes only one reflection from the CCD surface. Since the reflectivity of the LBNL CCDs might be as low as 2% this increases the signal to noise ratio dramatically. The goal is a 1% accuracy. We obtain good agreement between $1 - R$ and the direct QE results.

Keywords: CCD, quantum efficiency, reflectometer, reflectivity, calibration

1. INTRODUCTION

The previous paper[1] described the LBNL setup for measuring the quantum efficiency (QE) of CCDs. The CCD group at the LBNL has developed fully depleted backside illuminated CCDs which are optimized for higher infrared sensitivity. Accurate knowledge of their quantum efficiency provides important feedback for the design of new CCDs and their antireflective coatings. Also decisions of their usability in both ground-based and space-based missions require precise knowledge of the quantum efficiency.

The QE measurement is based on a calibrated photodiode. The CCD is illuminated with monochromatic uniform light. The QE is measured as

$$\mathrm{QE}_{\mathrm{CCD}} = \frac{S_{\mathrm{CCD}}}{G \cdot t \cdot I_{\mathrm{PD}}} \cdot \mathrm{QE}_{\mathrm{PD}} \cdot A_r \tag{1}$$

where S is the mean CCD signal in analog digital units ADU, G is the system gain here defined in ADU/e^-, t is the exposure time, I_{PD} the photocurrent of the calibrated photodiode, $\mathrm{QE}_{\mathrm{PD}}$ the quantum efficiency of the photodiode, and $A_r = A_{\mathrm{CCD}}/A_{\mathrm{PD}}$ is the area ratio between one CCD pixel and the photoactive area of the calibrated photodiode.

The uncertainties in exposure time and the area ratios are controllable. Due to the large number of pixels the mean signal also has a small uncertainty.

The QE of the calibrated photodiode is a rather problematic factor. We have to rely on the calibration of the manufacturer. Surface contamination of the photodiode may invalidate calibration of the photodiode. In similar setups, aging of calibrated photodiodes has caused inaccurate QE estimations.

Just as important is an exact knowledge of the system gain. Uncertainties of either the gain or the calibration are the most significant sources of systematic errors.

Since the goal for our measurement was to achieve a relative error of less than 1% and an absolute error of less than 3% we decided to implement additional measurements to crosscheck the QE data. The infrared

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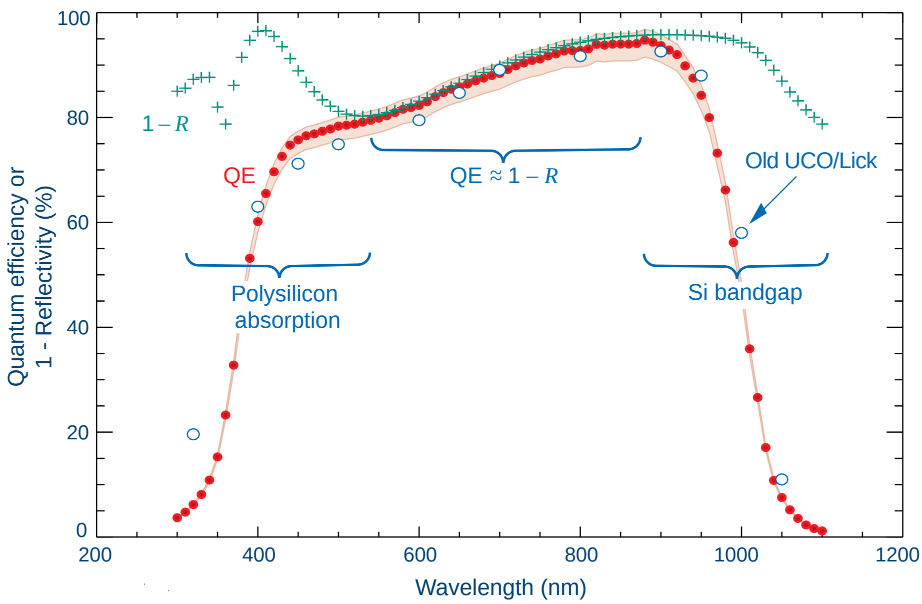

Figure 1. The quantum efficiency and one minus the reflectivity of the device 86136-7-7. For $\lambda > 900$ nm silicon becomes transparent (bandgap). For $\lambda > 600$ nm absorption in the polysilicon layer of the CCD becomes dominant. For 600 nm $< \lambda <$ 900 nm the QE is close to $1 - R$.

cutoff limits the quantum efficiency in the red. At about 900 nm the CCD starts to become transparent. In the blue, absorption in the backside polysilicon layer of the CCD becomes dominant. This effect reduces the QE for wavelengths below 500 nm. Between 500 nm and 900 nm we expect an internal quantum efficiency of close to 100% in the wavelength area below the infrared cutoff; i.e.,

$$\mathrm{QE} = 1 - R \tag{2}$$

where R refers to the reflectivity and T to the transmission. But more generally

$$\mathrm{QE} \leq 1 - R \tag{3}$$

must always be true. We have implemented a setup to measure R directly. Reflectivity is measured in two steps, first measuring the beam intensity and then measuring the intensity of the reflected beam.

2. THE QE MEASUREMENT

The QE setup was described in detail in [1]. Monochromatic light passes through a large integrating sphere to provide a uniform light field. A 80cm "drift space" between the sphere and the dewar turns the light exiting the sphere into almost parallel normally incident light on the CCD's surface. The CCD resides inside a dewar. Unlike in other QE setups, the calibrated photodiode is mounted right next to the CCD inside the dewar. The photodiode is temperature controlled to +25 C. This eliminates the need to calibrate the dewar window transmission. Also variations in the light intensity are seen by both the photodiode and the CCD.

3. WHY MEASURE THE REFLECTIVITY

The QE of the CCDs is directly derived from the signal of of calibrated photodiode, the CCD's signal and the QE calibration provided by the manufacturer. The calibrated photodiode was purchased from Hamamatsu. Hamamatsu does provide a "final inspection sheet" showing a plot of photo sensitivity vs wavelength and a table listing the photo sensitivity in mA/W and QE in %. Hamamatsu does not provide an estimate of the uncertainty of their calibration. Obviously this makes error estimates difficult.

We regularly open the dewar to exchange the device to test. Each opening of the system does brings dust into the system and onto the photodiode. We observe contamination of our dewar system, the photodiode and the CCD itself. Actual measurements of the QE showed variations of up to 7% within three different days. Other groups observed aging effects of their photodiodes.

The system gain measurement introduces another uncertainty. The gain calibration using ^{55}Mn K_α x rays from ^{55}Fe decay[2] became standard in the SNAP CCD group at the LBNL. Historically a conversion factor of 1620 e^-/γ is used. This number is based on the bandgap energy of 3.64 eV of silicon at room temperature. The number of measurements of the larger bandgap energy at -140$\tilde{C}$ which is the operating temperature of our CCDs are smaller in number. After a review of the existing literature[1] we moved towards using 1580 e^-/γ. Other gain measurements using a modified photon transfer[3] curve show good agreement with this number and an uncertainty of about 0.3%. Still, the gain measurement involves measuring the signal produced by each x-ray in the silicon and fitting a gaussian in order to obtain the mean signal. Depending on the chosen fiducial area of the CCD we found about 0.5% variation of the mean value, most likely due to imperfect background substraction.

These problems introduce significant systematic errors which are difficult to quantize. We set the goal for our QE measurement to achieve a relative error of 1% and an absolute error of 3%. Obviously this is not achievable without additional measurements of the QE.

4. SETUP

4.1. Basic principle

One well-known scheme to measure the CCDs is the VW scheme developed by John Strong,[4] illustrated in Fig. 2.

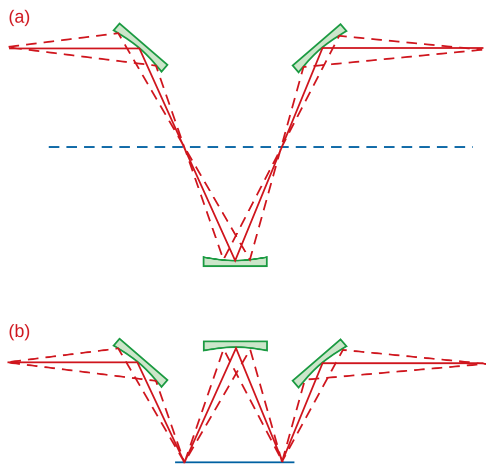

Figure 2. The VW scheme. a) First the monochromatic light beam is reflected off three mirrors giving the reference signal. b) Then the sample, here the CCD, is moved between the mirrors and one mirror is moved to the other side of the probe to give the reflected signal. The ratio of the both signals gives R^2.

The advantages of this system are that the only moving part is the one mirror which changes sides during the measurement and that all components involved in the reference measurement are also involved in the reflectivity measurement itself. Therefore no calibration of any of the mirrors or the photodiode is necessary and the setup is not sensitive towards variations like changes of the reflectivity of the mirrors. All these variations cancel out in the reflectance calculation.

A disadvantage is the need for two reflections from the probe's surface. Since our CCDs only have a reflectivity of a few percent, the signal-to-noise ratio becomes unfavorable. To get a larger signal a calibrated mirror may be put at the place of the second reflection, but this makes prior calibration of this mirror necessary. Therefore we

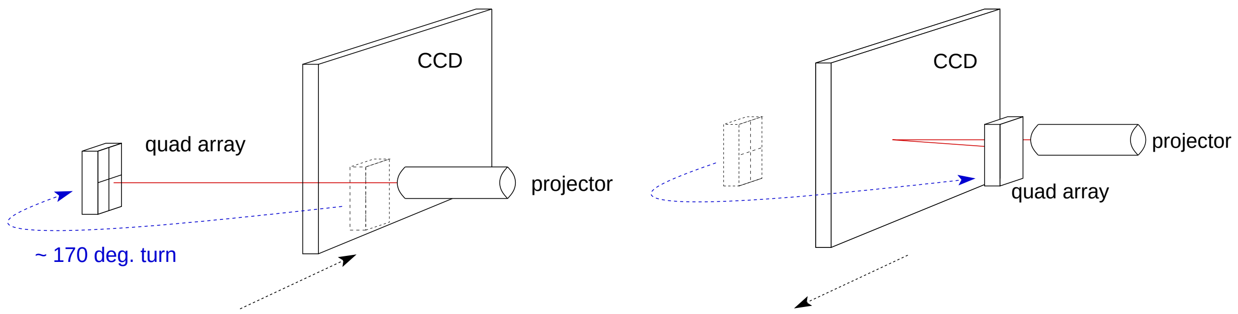

Figure 3. Left: The CCD is moved out of the optical path of the projector and the photodiode is moved in. The cumulative photocurrent gives I_0.
Right: The photodiode is moved out of the optical path and the CCD is moved in. The cumulative photocurrent gives I_{refl}. Then $R = I_{\text{refl}}/I_0$.

decided to design a setup which makes use of only one reflection, paying the price of having more moving parts. The measurement is done in two steps: Before measuring the actual reflected light, we first place the photodiode directly in the light beam of a spot point projector and record the beam light intensity I_0. In the second step we then project the light spot on the surface of the CCD. The reflected light is directly measured with a silicon photodiode to give I_{refl}. Then

$$R = I_{\text{refl}}/I_0 \tag{4}$$

Therefore we need to move the CCD into the beam path and turn the photodiode around the CCD. The light projector is fed by an optical fiber which connects it with a monochromator. A xenon arc lamp serves as light source. A feedback system assures light stability while taking the reference measurement and the actual reflectance measurement. The setup implements several safety mechanisms to prevent the CCD from being harmed, so it allows us to measure the reflectivity of actual science grade devices.

4.2. Detailed description

4.2.1. Light source

We used the monochromator and the arc light source (100W xenon light bulb) from the QE setup described in [1]. The xenon arc lamp was chosen to provide more light intensity in the UV. Optical filters eliminate stray light and suppress second-order refracted light. The monochromator is equipped with a motorized input slit and a fixed output slit at the lateral port.

Spectra Physics provides a “Digital Exposure Controller” which uses feedback to stabilize the light level. It comes with a temperature-controlled photodiode to provide the feedback signal.

We decided not to use a fiber with enhanced UV transmittance, since we do not expect a match of the QE with $1 - R$ in the UV due to absorption in the polysilicon layer of the CCDs. So we lose the UV part from the xenon.

4.2.2. Projector and feedback

We measure the reflectance at an incident angle of 7°. Therefore in the reflectivity measurement position the beam projector and the photodiode are separated by an angle of 14°. The beam projector was adopted from an old wire bonder, where it served as crosshair projector. We took the crosshair mask out and replaced it by a 1 mm aperture mask. The projector has a focal length of about 7.8 cm. We made a beamsplitter which attaches to the end of the projector. The optical fiber feeds into the beam splitter. We disassembled the feedback photodiode box from the Spectra Physics “Digital Exposure Controller” and build the photodiode into the beamsplitter. The result is a compact projector/feedback assembly which is mounted using an mirror mount. The mirror mount has fine-adjustment micrometers for two axes which allow us to center the light beam on the photodiode.

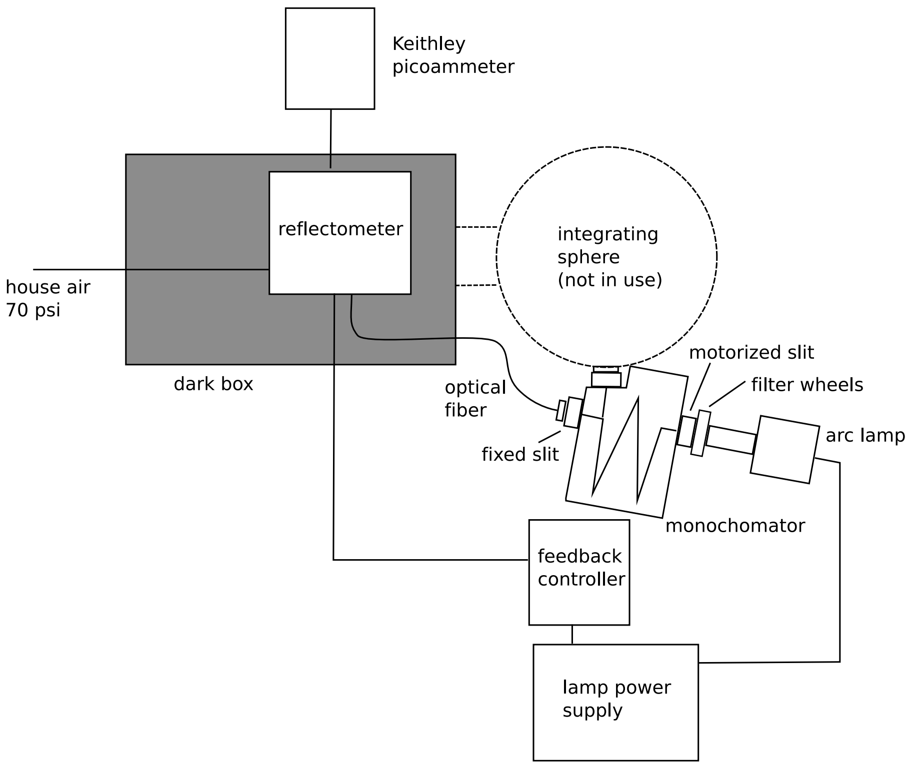

Figure 4. The reflectometer setup. The lightsource, monochromator and dark box are the same as in the QE setup. The reflectometer resides in the dark box.

4.2.3. Photodiode quad array

It is important to capture the whole beam diameter at both measurement positions. Therefore, instead of using a single photodiode, we use a quad array. Using a simple summation/difference circuit we can center the light beam precisely on the photodiode.

The quad array is mounted on a lever which is attached to a rotary pneumatic actuator. The actuator turns the photodiode between the two measurement positions.

A reed switch interlock assures that the photodiode can not accidently be moved into the beam path while the CCD is still in position.

4.2.4. CCD stage

The CCD is first mounted on a two-axis tilt platform, allowing the reflected beam to be centered on the quad array. This assembly is mounted on additional slides for focus adjustment and selection of the vertical position of the actual point on the CCD's surface where the reflectivity is to be measured. Finally everything is mounted onto a pneumatic slide which allows the CCD to be moved back and forth between both measurement positions. By adjusting the endpoint of the slide the horizontal position of the point to measure the reflectivity is selected. Again a reed switch makes sure that under no circumstances can the CCD and the photodiode collide.

4.2.5. Automation

The pneumatic stage of the CCD and the rotary actuator of the photodiode are connected to an electrically controlled pneumatic manifold. We built a circuit with a microcontroller (PIC) to allow communication with a PC over the serial port. Finally a JAVA program controls and automates the measurement.

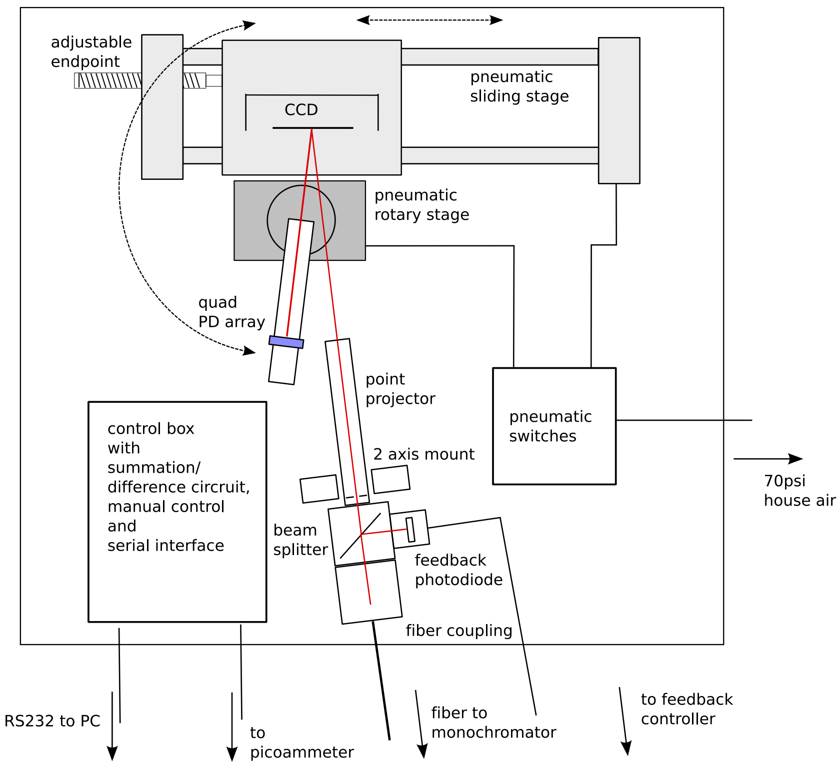

Figure 5. The reflectometer. The CCD is mounted on a pneumatic sliding stage. It can be adjusted for tilt around two axis and for focus. A point projector equipped with a feedback assembly for light stabilization provides the probing beam. A quad-array photodiode measures first the light beam directly then the reflected beam. Using a quad array allows careful beam centering.

4.2.6. Signal measurement

The total photocurrent of the quad array is measured by a Keithley picoammeter. The serial port of the picoammeter allows communication with the control software.

4.2.7. Dark box

The reflectometer resides in a dark box, the same box which provides the 80 cm drift space for the QE setup. There are electrical feedthroughs at the ends of the dark box for communication with the PC and the picoammeter.

5. MEASUREMENT PROCEDURE

5.1. System setup

The CCD is placed in a box assembly to protect it from ESD damage, being touched or collecting dust. Only after the box is attached to the CCD stage is the lid is taken off and the CCD exposed the ambient air.

The actual location on the surface of the CCD where the reflectivity is to be measured is then selected. The setup allows any spot on a surface of 5cm by 5cm to be chosen.

5.2. Centering

To assure that the photo diode array actually captures of the whole light beam, the light beam has to be carefully centered on the quad array. The monochromator is first set to a convenient wavelength. Using visible light simplifies the procedure. The slitwidth of the monochromator input port is set to its maximum.

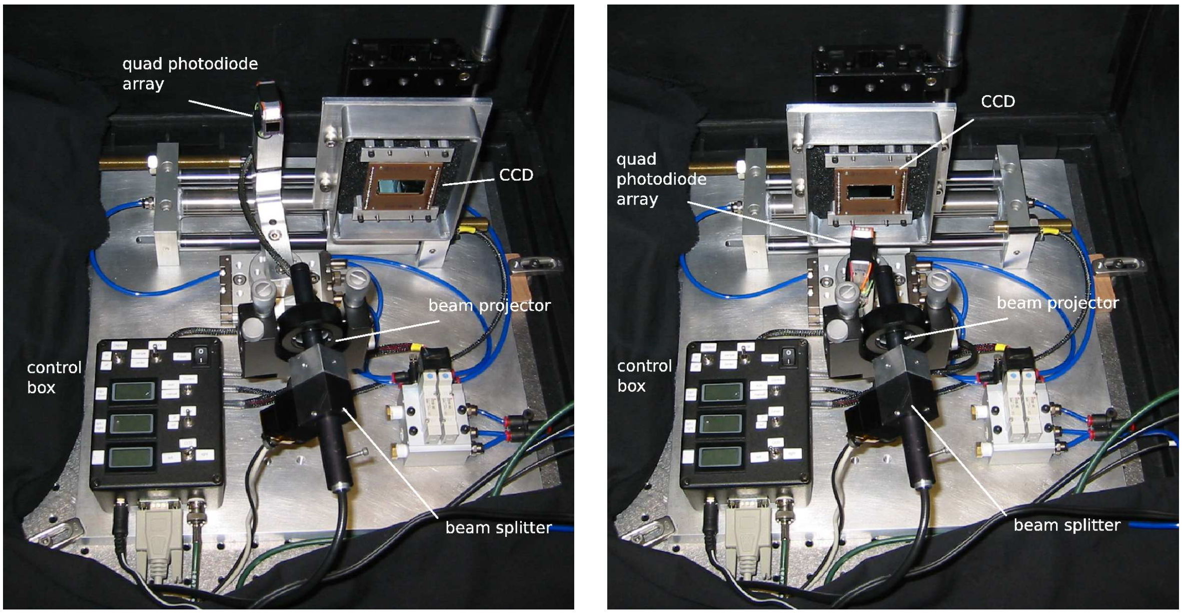

Figure 6. The actual reflectometer. A CCD is mounted to be tested.
Left: Reflectometer is in position to record I_0 the photodiode faces the beam projector directly.
Right: The I_{refl} measurement mode. The light beam from the projector reflects off the CCDs surface and gets intercepted by the photodiode.

Displays on the control box show the differential signal of the left and right half of the quad array and the difference of the top and the bottom half signal. A third display shows the overall signal. Toggle switches allow selection between manual control of the setup and automatic control i.e. the computer. In the manual mode, the CCD slide and the photodiode lever are operated using switches. The photocurrents of the four diodes in the quad are selected to be processed either by the summation/difference circuit or to be measured in parallel by the picoammeter.

At first, the setup is adjusted for the reference measurement. The photodiode lever is positioned for the reference measurement i.e. the photo diode array is placed so that it directly faces the projected beam. Using the micrometers of the projector mount, the light beam is centered on the quad array. Then the CCD and the photodiode are positioned for reflectance measurement. The CCD now faces the projector. The light beam reflects of the CCD's surface. The quad array is placed close to the projector output. Using the tilt platform on which the CCD is mounted, the light beam is again centered on the quad array.

5.3. Measurement

For each selected wavelength control the software records the dark current I_{dark}, the reference light intensity I_0 and the reflected light intensity I_{refl}. We chose to take 10 current samples for each measurement of I_{dark}, I_0 and I_{refl} with one second integration times.

As a first step the software positions the CCD and the photo array in a neutral position. The dark current I_{dark} from the photodiode is recorded. The photodiode array is then positioned in the light path so that it faces the beam projector and I_0 is recorded. For the actual reflectivity measurement the CCD is then moved into the beam path. The photodiode array is positioned next to the beam projector facing the CCD and I_{refl} is recorded. Finally the reference measurement is repeated to verify the light stability.

Table 1. Part list for the LBNL reflectivity measurement setup. A detailed description for the monochromator and the light source can be found in.[1]

Part	Manufacturer	Model
Light source		
Monochromator	Spectra Physics	MS257 77700a
Gratings	Spectra Physics	see [1]
Optical filters	Spectra Physics	see [1]
Arc lamp housing	Spectra Physics	66901
Arc lamp power supply	Spectra Physics	69907
Xenon 100W light arc light bulb	Spectra Physics	6257
Digital exposure controller with feedback photodiode	Spectra Physics	68945
Point projector		
Modified crosshair projector from wirebonder	Volpi	-
In-line mirror mount	Opto Sigma	112-2630
CCD stage		
Tilt platform	Opto Sigma	123-2240
Sliding stage	Newport	423
Sliding stage	Newport	433
Right angle bracket	Opto Sigma	123-8130
Rodless pneumatic slide	Bimba	Ultran USS-0605.000-A1
Quad array		
Quad photo array 2x2 elements 10x10mm active area	Hamamatsu	S5981
Adjustable-angle rotary air actuator	SMC	MSQB10A-DIH00456
Current meter		
Picoammeter	Keithley	6485

6. RESULTS

6.1. Reflectance measurement for silicon

We first measured the reflectivity of a piece of unprocessed silicon i.e. a wafer (see Fig. 7). The wafer was HF etched for three hours before the measurement started to eliminate possible surface contamination. In the wavelength range from 400 nm to 1000 nm we get good agreement with the theoretical value of the reflectivity calculated as:

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \tag{5}$$

where the refactive index n was taken from the Handbook of Optical Constants of Solids[5] and the absorption for room temperature k was calculated using the parameterization from Rajkanan, Singh, and Shewchun.[6]

6.2. Reflectivity measurement for device 86135-7-7

We then measured the reflectivity of a thick, fully depleted CCD developed at the LBNL. As shown in the introduction in Fig. 1 we get good agreement with the QE measurement for the device.

Also our reflectivity measurement agrees well with the data from the UCO/Lick observatory as shown in Fig. 8.

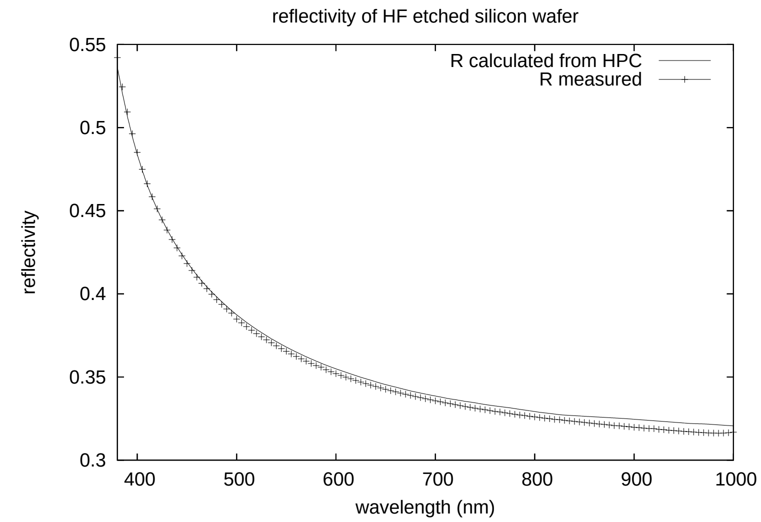

Figure 7. Shows the measured reflectivity of a piece of a silicon wafer and the calculated reflectivity. The wafer was HF etched before the measurement to eliminate surface contamination. The measured and the calculated curve show good agreement. The absolute difference is not lager than 0.005.

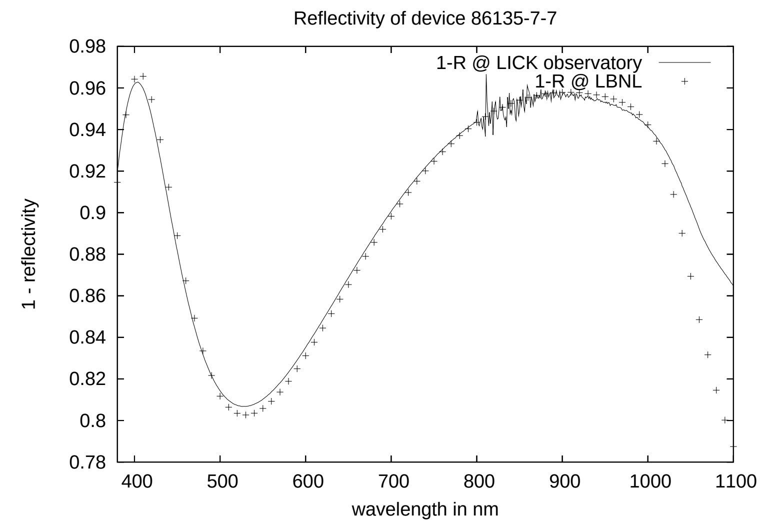

Figure 8. $1 - R$ for device 86135-7-7 measured at LBNL and the UCO/Lick observatory.

6.3. Repeatability

To test the setup for repeatability we measured the reflectivity for a selection of wavelengths 10 times in one day. The largest fractional standard deviation we found for ten consecutive measurements was 0.3% for 1000 nm. To test the longterm stability we repeated the reflectivity scan for one device with a three month time interval between the two tests. Figure 9 shows curves taken of the same device in September and in December.

7. SOURCES OF ERRORS

The noise for the photocurrent measurement is negligible, and the variations in the light intensity are very small. The standard deviation for the ten samples of I_{refl} at each wavelength is shown in Fig. 10 to be never greater than 0.02%. The signal to noise ratio for I_0 is larger.

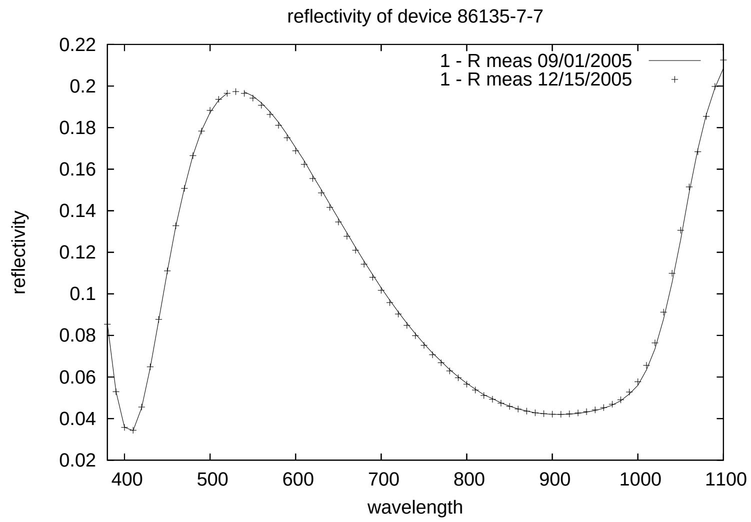

Figure 9. The two measurements of $1 - R$ for device 86135-7-7 match well.

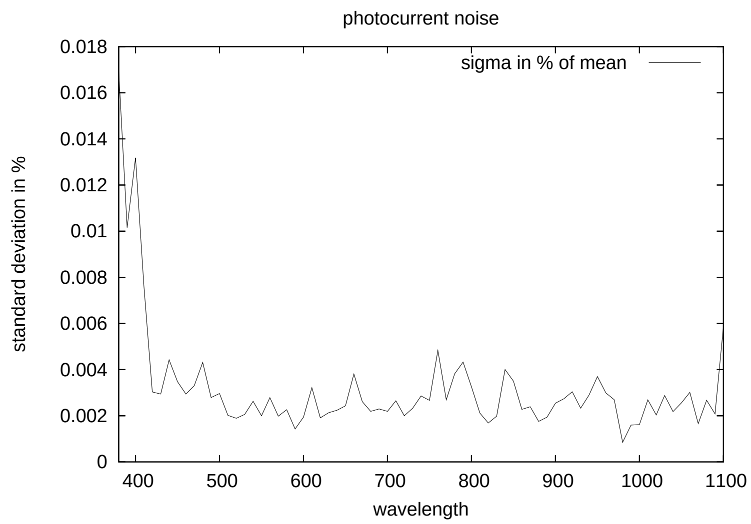

Figure 10. Shows the noise of I_{refl} form one scan.

Even though the visible spot is not larger than about 3 mm in diameter, one concern was that the light spot might actually be larger than the 10 mm by 10 mm photodiode, so that the photodiode does not intercept the whole beam. After having centered the beam on the quad array, we moved the spot using the micrometers on the mount of the light projector and observed the output on the picoammeter. We found the light intensity to be insensitive to small movements of the spot.

Since the reflectivity is measured at an incident angle of 7° but the QE is measured for light of normal incident angle a slight difference between QE and $1 - R$ is to be expected. The antireflective coatings were developed for light of normal incident angle. Light of different incident angle will increase the length of the beam path through the coating layers and therefore cause a change of the measured reflectivity.

Also since we probe with a cone shaped light beam, we actually integrate over an angular range of about 3.5° to 11.5°.

8. CONCLUSION

We incorporated an automated setup to measure the reflectivity of our CCDs into the QE Machine. The reflectometer shows very stable results which are in good agreement with the expected values in the wavelength range from 380 nm to 1000 nm.

Therefore we expect to be able to use the data as a cross check for our QE estimations. We got good agreement with another group for the reflectivity of an actual CCD.

Our reflectivity implementation takes several measures to prevent the CCDs from being harmed. Therefore we will be able to use it on a regular basis to support the QE measurement.

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