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Silicon photodiode device with 100% external quantum efficiency

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A device utilizing four inversion layer photodiodes in a light-trapping arrangement was constructed and tested. The device was found to have a photon-to-electron conversion efficiency of 0.999 for short wavelength and low power visible radiation. It was found that applying a reverse bias voltage extended the high quantum efficiency response over the entire visible spectrum and up to the highest radiant power level studied (several milliwatts). Several radiometrically important characteristics were studied and the results presented: spectral reflectance; polarization sensitivity; quantum efficiency vs wavelength, photon flux density, and reverse bias voltage; and dark current vs reverse bias.

I. Introduction

A technique for predicting the external quantum efficiency (photon-to-electron conversion efficiency) of a silicon photodiode in the 380–900-nm spectral region was developed recently and demonstrated to be very accurate[1,2] and quite simple[3] compared with conventional thermal radiometric techniques. For the photodiodes used in those studies the principal loss mechanisms in the photon-to-electron conversion process are the loss of photons due to reflection at the front surface and the loss of minority carriers due to recombination. Recombination losses can be characterized by the three regions in which they occur: (1) at the SiO_2–Si interface; (2) in the front volume between the interface and onset of the depletion region; (3) in the rear volume outside the depletion region. Recombination losses in Region 1 can be measured by the oxide bias method.[4] In Region 2 the recombination losses are small and can be neglected except at short wavelengths.[2] In Region 3 it has been shown that recombination losses can be eliminated by applying a reverse bias voltage[4] to extend the depletion region.

It has also been shown that for an inversion layer type of silicon photodiode the recombination losses at the interface and in the front volume are negligible.[5] The inversion layer silicon photodiode was developed by Hansen[6] and is now manufactured by United Detector Technology. In this type of photodiode the junction is induced in the Si by positive charges trapped in the SiO_2. The front region minority carriers (holes) are repelled from the SiO_2–Si interface by the trapped positive charge and swept across the junction by the field within the depletion region before a significant amount of recombination can occur.

For short-wavelength photons that are entirely absorbed in the front region, the only significant loss in an inversion layer photodiode is that due to reflection. With the application of a reverse bias voltage, the range over which this is true can be extended to longer wavelengths. In this paper we will describe a simple light-trapping arrangement of several inversion layer photodiodes that eliminates the loss due to reflection. The external quantum efficiency of this device has been measured and found to be 0.999 ± 0.002 in the 400–700-nm wavelength range.

Because of its potential as an absolute radiometric standard we have examined several characteristics of a small sampling of the inversion layer photodiodes used in the multiple detector devices as well as some of the characteristics of the overall device. The various characteristics studied and presented in this paper are: the geometrical properties, that is, the shape and size of the field of view of this particular configuration and its approximate relationship to the spectral variation of reflectance; the effect of the reflectance on quantum efficiency and polarization sensitivity; the wavelength variation of the quantum efficiency; the effect of reverse bias on the quantum efficiency; the effect of photon flux density on the quantum efficiency; and the effect of reverse bias on the dark current in inversion layer photodiodes with a comparison with other types of silicon photodiode. Finally, we discuss several possible improvements for future generations of multiple inversion layer photodiode devices plus a possible 100%

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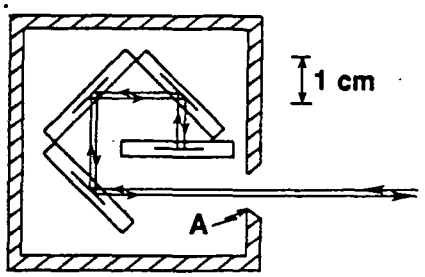

Fig. 1. Optical configuration of the four photodiodes (top). The reflected light beam is shown displaced from the incident beam for clarity of illustration.

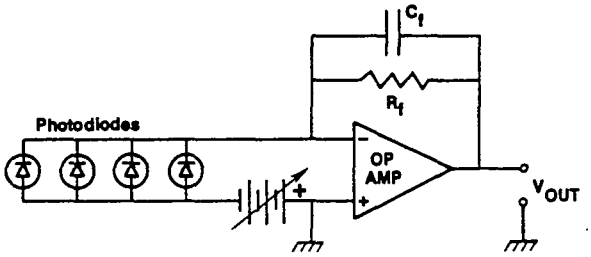

Fig. 2. Electrical configuration of the four photodiodes, dc bias, and operational amplifier.

quantum efficient device based on the more widely used p-n type of silicon photodiode.

II. Experiment

The light-trapping arrangement used in this study is illustrated in Fig. 1. Three windowless photodiodes were set at 45° to the incident radiation so that the reflected radiation from the first photodiode was incident on the second and so on. A fourth windowless photodiode was set at normal incidence so that the radiation was reflected back along the original path. The radiation, therefore, was incident on seven surfaces before exiting the device.

The active area of the silicon photodiodes was 1 cm^2 (circular). In the arrangement depicted in Fig. 1 the angle subtended by the last reflecting surface from a point on the first surface is 4.2° in the plane of the reflections and 5.9° perpendicular to this plane. For a 0.1-cm^2 aperture at the plane of the entrance to the housing (point A in Fig. 1), the field of view at 1 m from this aperture would be an ellipse with major and minor diameters of 5.0 and 2.7 cm, respectively. At 50 cm from the aperture the major and minor diameters would be 2.3 and 1.2 cm. This is the minimum field of view. Because of the lower reflectance at long wavelengths, as will be discussed later, complete absorption is accomplished in fewer than seven reflections, and in the long-wavelength region the field of view will be considerably larger.

The output currents of the four photodiodes were summed by connecting them in parallel. The total output current was measured using a low noise operational amplifier in the configuration shown in Fig. 2. The gain of the amplifier was calibrated within an uncertainty of <0.05%. A variable dc power supply was connected in series with the photodiodes to produce the reverse bias needed to restore 100% collection efficiency at high radiant flux levels and/or long wavelengths. A word of caution: depending on the dc power supply, its placement in the circuit, and the magnitude of the feedback resistor, ground loops and feedback oscillation are potential problems. Such problems can be detected by monitoring the amplifier output with an oscilloscope.

The external quantum efficiency was measured at four laser wavelengths: 406.7, 676.4, and 799.3 (krypton-ion laser), and 632.8 (He–Ne Laser) nm. These were amplitude stabilized[7] cw lasers. As a further step to improve the long-term laser stability and increase the precision of the measurements, a separate silicon photodiode was used to monitor the laser beam power and correct for residual drift.

Except for the 406.7-nm line, the laser beam power in the 1–2-mW range was measured with both a self-calibrated silicon photodiode[1,2] and an electrical substitution thermopile radiometer.[8] Because the amount of recombination occurring in Region 2 cannot be accurately estimated and, for 406.7-nm radiation, is too large to be neglected for the p-n type of photodiode used in the self-calibration, the electrical substitution thermopile radiometer was the sole absolute basis of the 406.7 nm measurement. The estimated uncertainty of the quantum efficiency as measured with either technique was ±0.2%. Both measurement methods agreed to well within the estimated uncertainties.

With a known radiant power input ϕ and measurement of the photocurrent (output current minus the dark current) I, the external quantum efficiency Q is obtained by

$$Q = \frac{I \cdot h \cdot c}{\phi \cdot n \cdot e \cdot \lambda}, \tag{1}$$

where h is Planck's constant, c is the velocity of light, n is the index of refraction of air, e is the elementary electronic charge, and λ is the wavelength of the laser radiation. In the visible region of the spectrum

$$\frac{h \cdot c}{n \cdot e} = 1.2395 \times 10^3 \text{ (W nm A}^{-1}\text{)}. \tag{2}$$

At radiant power levels below 1 mW, a p-n silicon photodiode (the type used in the self-calibration procedure) was used as the basis of the measurement. The high degree of linearity of the responsivity of these silicon photodiodes (<0.1% deviation in 8 decades) has been well verified.[9–11] The uncertainty in these measurements was dominated by the precision of the comparison between the single photodiode and the multiple photodiode device.

The photodiodes had a thermally grown SiO_2 layer on the front surface acting as an antireflection coating. The thickness of this layer was estimated by measuring at 406.7 nm the reflectance of the first photodiode in two of the multiple detector devices. This was done by measuring the photocurrent I_1 from the first photodiode by blocking the radiation from reaching the last three

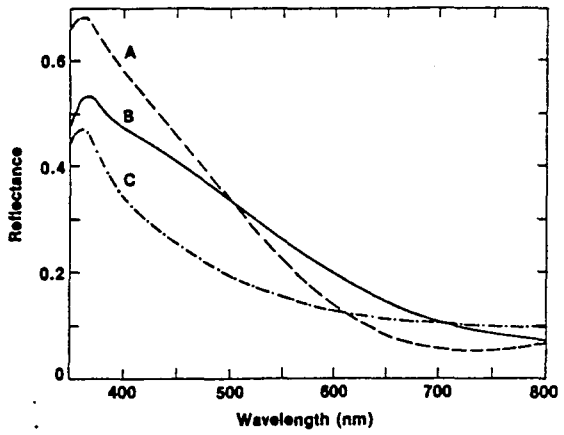

Fig. 3. Spectral variation of the reflectance of a 140-nm thick layer of SiO_2 on Si: *A*, TE polarized 45° angle of incidence; *B*, 0° incidence; *C*, TM polarized 45° incidence.

photodiodes. Then by unblocking the beam, the photocurrent from all four photodiodes I_t was measured. Since the quantum efficiency is equal to the fraction of photons transmitted into the SiO_2 (i.e., one minus the reflectance) and if the difference in reflectance between 45 and 0° incidence is neglected, the reflectance ρ can be approximated as follows:

$$\rho \simeq 1 - (1 - \rho^7)I_1/I_t \simeq 1 - (I_1/I_t). \quad (3)$$

At other than normal incidence the reflectance varies with polarization. The photodiode reflectance was measured in both the TE (electric vector transverse to the plane of reflection) and the TM (transverse magnetic) modes. The thickness of the SiO_2 layer was calculated[12] using the real and imaginary indices of refraction[13] of Si and the real index of refraction[14] of SiO_2. For four reflectance measurements the SiO_2 thickness estimates varied from 138 to 148 nm. The nominal thickness was chosen to be 140 nm.

III. Results

Figure 3 shows the calculated reflectance of a 140-nm thick layer of SiO_2 on Si for 0 and 45° incident radiation in the 350–800-nm wavelength range. Using these reflectance values one can predict the quantum efficiency as a function of wavelength. This is shown in Fig. 4 for the detector configuration used in these experiments. It has been assumed that nonspecular reflection losses are negligible. For TM polarized radiation, the calculated external quantum efficiency is 0.999 at 406.7 nm, increasing to 1.000 within 10 nm. For radiation polarized in the TE mode, the calculated quantum efficiency at 406.7 nm is 0.986, increasing to 1.000 at 500 nm. The calculated quantum efficiency in the 350–365-nm region includes the increase of the quantum yield above unity due to impact ionization.[15]

Note that at long wavelengths the light does not have to be incident on all seven surfaces before a negligible reflection loss is obtained. For example, for unpolarized light at 550 nm a quantum efficiency of >0.999 is obtained with only five reflections. Therefore, due to the configuration of this device, the longer the wavelength the greater the field of view.

The quantum efficiency at 406.7 nm in the TM polarization was measured on two devices and found to be 0.999 for both of them. In the TE polarization the measured quantum efficiencies were 0.988 and 0.989. This is in excellent agreement with the predicted value. At 632.8 and 676.4 nm the measured quantum efficiency was 0.999, which is also in excellent agreement with the prediction. The measurements at 406.7 nm were made with a reverse bias of 10 V; at 632.8 and 676.4 nm, the reverse bias used was 20 and 40 V, respectively. A reverse bias was necessary to offset the forward bias current and to overcome the recombination trap effect, as will be discussed below. A third device that demonstrated a reasonably low dark current level at very high reverse bias was measured at 799.3 nm and found to have a quantum efficiency of 0.990 at 100 V. An extrapolation (see below) indicated that 100% quantum efficiency would be obtained at ~180-V reverse bias, which was well beyond the limits of our dc power supply.

At high photon flux levels the flow of photogenerated charge carriers in the relatively high resistance inversion layer produces a forward bias. This generates a forward current which offsets the collection current. This is the mechanism of the saturation nonlinearity in silicon photodiodes.

The recombination trap effect is related to the other type of silicon photodiode nonlinearity: suprarresponsivity. This manifests itself as an increase in quantum efficiency with increasing radiant power. It is caused by the filling of recombination traps with photogenerated minority carriers. The carriers are trapped for some time before recombination occurs, thus deactivating the site. As the recombination traps are filled the minority carrier lifetime increases, thereby increasing the number of minority charge carriers collected at the junction.

The quantum efficiency measurements reported above were made at radiant power levels of 1.6–2.2 mW

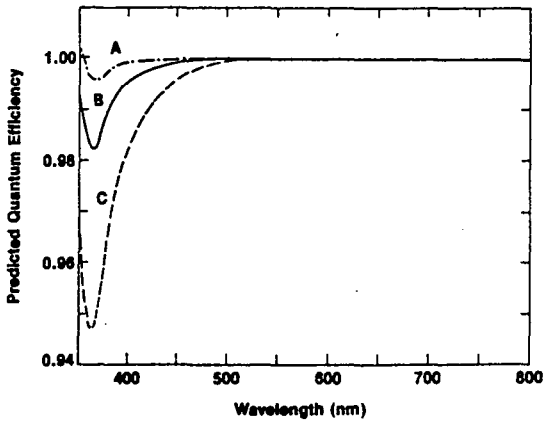

Fig. 4. Predicted quantum efficiency of the four photodiode light-trapping devices used in this study: *A*, TM polarized input; *B*, unpolarized; *C*, TE polarized.

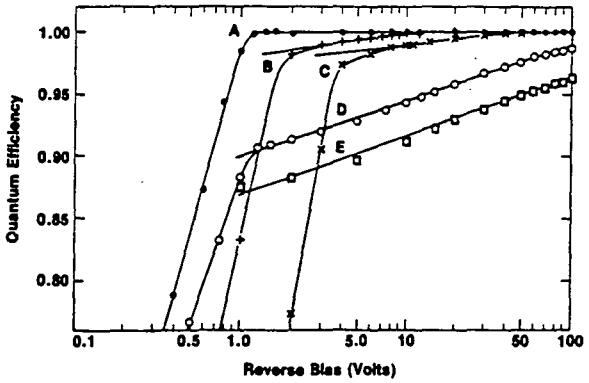

Fig. 5. Measured quantum efficiency at several wavelengths as a function of reverse bias voltage (see Table I): *A*, 406.7 nm; *B*, 632.8 nm; *C*, 676.4 nm; *D*,*E*, 799.3 nm. Curves *A*–*D* were obtained with a radiant power of ~2 mW, *E*, ~20 μW.

Table I lists the wavelengths and radiant powers used for each curve in Fig. 5. Also included are the slopes (base 10 logarithm), intercepts, and correlation coefficients that resulted from a linear regression analysis of the data in the region from the forward current offset to attainment of 100% quantum efficiency. Device I was also measured at 676.4 nm; the results are listed in the table but not in Fig. 5.

A number of observations can be made from Fig. 5 and Table I regarding these data. The variation of quantum efficiency due to the recombination trap effect is quite linear with respect to the logarithm of the reverse bias voltage as can be seen from the correlation coefficients which are close to unity. The amount of bias voltage required to offset the forward current is different for each device (i.e., it is photodiode dependent) but is independent of wavelength. The slope of

Table I. Experimental Conditions Used in Generating Fig. 5 and Results of a Linear Regression Analysis

Curve/device	Wavelength (nm)	Radiant power (mW)	Voltage at forward current offset (V)	Intercept	Slope	Correlation coefficient
A/I	406.7	2.2	1.3	—	—	—
B/II	632.8	1.9	3	0.981	0.0177	0.998
C/III	676.4	1.9	10	0.974	0.0155	0.979
D/I	799.3	1.6	1.3	0.900	0.0442	0.999
E/I	799.3	0.016	0	0.870	0.0462	0.996
[a]/I	676.4	2.0	1.3	0.979	0.0153	0.982
[a]/I	676.4	0.017	0	0.976	0.0123	0.989

[a] Curve not shown in Fig. 5.

in a spot 3–4 mm in diameter. At 406.7 nm it was found that, depending on the device, 1–10-V reverse bias was required to offset the forward current due to the high flux density. The forward current effect occurs at all wavelengths, whereas the recombination trap effect occurs only at long wavelengths. To overcome the recombination trap effect at 632.8 nm, 10–20-V reverse bias was required; at 676.4 nm, it was 30 to 40 V; and at 799.3 nm, an extrapolation indicated that ~180 V would be necessary. However, this photodiode would probably have broken down and become conductive before the optimum voltage was reached.

Figure 5 shows the quantum efficiency vs reverse bias at the four wavelengths studied. This is a rather busy figure, but it is included in this form to show several effects that are obvious when the data are examined in this grouping. Table I should also be consulted when examining this figure. Curves *A*, *B*, and *C* were obtained with three different multiple detector devices I, II, and III, respectively. Curves *D* and *E* were obtained with Device I. The differences between the devices is due to the differences among the particular photodiodes used in the devices. Devices I and III used inversion layer photodiodes selected for low dark current at high reverse bias. For Device II, the maximum usable reverse bias was ~17 V. No information was available regarding fabrication differences among the various photodiodes used.

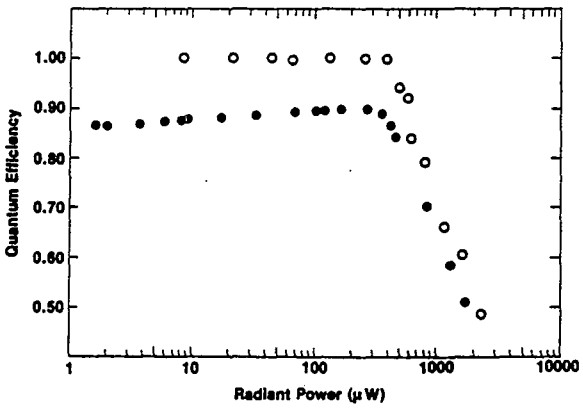

Fig. 6. Measured quantum efficiency as a function of radiant power level at 406.7 nm ○ and 799.3 nm ●.

the linear region is wavelength dependent. The amount of bias voltage required to achieve 100% quantum efficiency is wavelength dependent; higher bias voltages are required at longer wavelengths. Finally, at long wavelengths and low radiant power, higher reverse bias voltages are required to achieve 100% quantum efficiency.

Figure 6 is a plot of the quantum efficiency measured at two wavelengths as a function of the radiant power at zero reverse bias. This plot illustrates both the effect of the saturation nonlinearity and, for the 799.3-nm

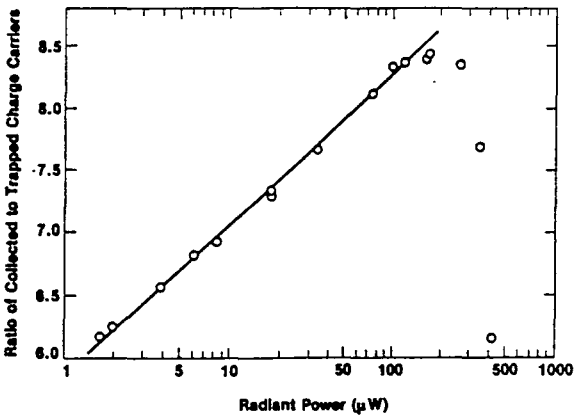

Fig. 7. Ratio of collected to trapped photogenerated charge carriers as a function of radiant power level at 799.3 nm.

type by curves *C* and *E*, and the boron doped *p-n* type by curves *A*, *F*, and *G*. The photodiodes used in two of the three multiple detector devices studied were selected for low dark current at high reverse bias represented by curve *D*; the other one had a dark current behavior represented by curve *B*. The difference in the dark current between the *p-n* and the *n-p* type of photodiode is most likely due to leakage current along the SiO_2–Si interface and out to the edges of the chip. In the *p-n* photodiodes, the positive charge layer in the SiO_2 repels the majority charge carriers away from the interface thereby impeding the reverse current. A guard ring on the *n-p* and inversion layer photodiodes would have a similar effect and might produce a substantial reduction in the dark current. Curve *A* is included to show that some *p-n* photodiodes can have very high dark current under reverse bias. This photodiode would not be suitable for many radiometric applications. At zero reverse bias the dark current of