Temperature dependence of the quantum efficiency of silicon $p-n$ photodiodes

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The temperature dependence of the quantum efficiency of silicon $p-n$ photodiodes for photon energies of 1.1–5.2 eV is measured in the temperature range 77–300 K. It is shown that for photons with energies exceeding 1.4 eV the change in quantum efficiency is less than 0.01% per degree. The temperature dependences of the photoresponse of silicon photodiodes and of GaAs and GaP Schottky barrier photodiodes are compared. © *1999 American Institute of Physics.* [S1063-7826(99)01903-1]

1. Silicon $p-n$ structures and GaAs and GaP Schottky diodes are the most widespread ultraviolet semiconductor photodetectors.[1,2] These devices have the common shortcoming of a sharp drop in quantum efficiency at short wavelengths. An additional drawback of the GaAs and GaP devices is that they have a strong temperature dependence of the photocurrent, which increases severalfold as the temperature is raised from 100 to 300 K.[3,4]

We are unaware of any experimental papers in which the temperature dependence of the quantum efficiency of silicon $p-n$-structures has been studied in a wide range of temperatures. In this paper we report the results of such a study. Our experiments show that in the short-wavelength interval corresponding to 1.4–5.2 eV, the quantum efficiency is essentially independent of temperature. In the long-wavelength interval corresponding to 1.1–1.3 eV, there is a strong temperature dependence apparently due to the increased number of photons required for an indirect optical transition.

A model has been proposed[3,4] to explain the rapid rise in the photocurrent with temperature. According to this model, photocarriers are captured at traps located in the space charge region. This sort of trap presumably is capable of simultaneously capturing an electron and a hole, so that, at low temperatures, a large fraction of the photocarriers recombine at traps, while the remainder are ejected from the trap by thermal excitation. This fraction of the photocarriers also contributes to the photocurrent, which increases with temperature. The experimental results and their explanation given in Refs. 3 and 4 indicate that there is an extremely high concentration of traps in the space charge region. Estimates show that atomic traps should have a concentration on the order of 10^{19} cm^{-3}, so that probably these traps are two-dimensional, like dislocation loops.

The absence of an increase in the photocurrent with temperature in silicon $p-n$ structures is, we believe, of fundamental importance. It is evidence of a high technological and design perfection in the silicon structures and of the absence of any structural defects in their space charge regions.

2. The objects of study were silicon photodiodes prepared by local diffusion from the gaseous phase. An initial n-Si:P substrate with a [100] orientation and a specific resistance of 20 $\Omega\cdot$cm was oxidized in dry oxygen in the presence of chlorine-containing substances. After oxidation a 7×7 mm window was opened up and boron was diffused into it to a depth of $\leqslant 30$ nm. Here the impurity concentration in the layer near the surface was determined by Rutherford backscatter spectroscopy (RBS) to be $N_A(0) \approx 10^{22}$ cm^{-3}. An isotypic $n-n^+$ junction was created on the opposite side. Metal contacts were formed on the front using photolithographic techniques and etching of a vacuum-deposited aluminum film.

Figure 1 shows the spectral characteristic of a photodiode of this type. An analysis of the quantum efficiency spectrum of this photodiode along with the reflection spectrum of silicon[5] shows that the inner quantum efficiency of the detector is close to unity. This type of detector can operate in the ultraviolet.

A model of similar highly asymmetric silicon $p-n$ junctions with ultrashallow doping has been examined by Redfield.[6] A high electric field $E > 10^4$ V/cm, which extends up to the outer surface of the doped region of the $p-n$ junction, ensures that the carriers generated in this region drift at a high velocity, close to the maximum saturation value of $\approx 10^7$ cm/s. The time over which a carrier generated near the surface reaches the $p-n$ junction is $t \leqslant 3$

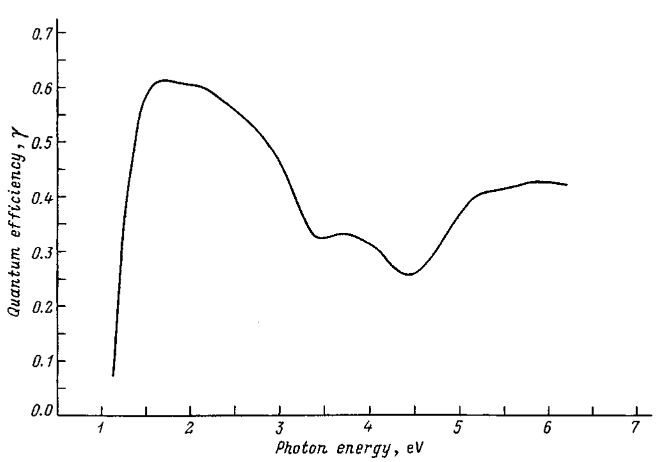

FIG. 1. The quantum efficiency of a silicon photodiode (in electrons per photon) as a function of photon energy at room temperature.

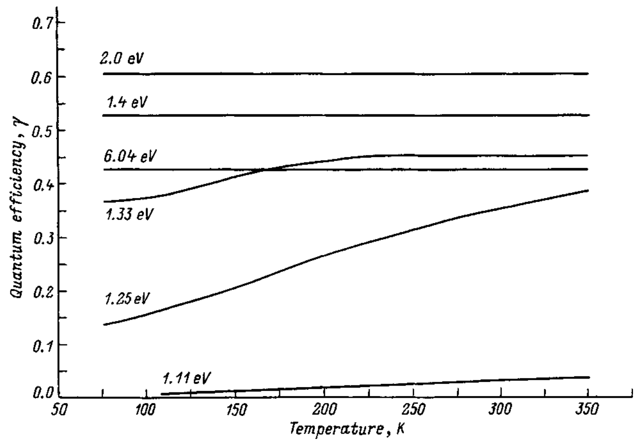

FIG. 2. Quantum efficiency of a silicon photodiode (in electrons per photon) as a function of temperature at several photon energies.

$\times 10^{-13}$ s. These short drift times explain the low level of recombination losses in the thin, highly doped region of the $p-n$ junction.

3. The results of the experiments are reflected in Fig. 2 and reduce to the following.

For photon energies of 1.1–1.3 eV, the quantum efficiency increases with rising temperature, and more rapidly for lower energy photons. We assume that this is related to an increase in the number of photons, since when the photon energy slightly exceeds the band gap, the indirect optical transitions mainly involve absorption of a photon.

For photon energies of 1.4–5.2 eV, the quantum efficiency is temperature independent. Since the error in the measurements was less than 1.5%, we may conclude that in this region of the spectrum the change in the quantum efficiency is less than 0.01%/°C.

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