Far infrared photoelectric thresholds of extrinsic semiconductor photocathodes

A. G. U. Perera, R. E. Sherriff, M. H. Francombe, and R. P. Devaty
Applied Technology Laboratory, Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

(Received 3 December 1991; accepted for publication 7 April 1992)

Far infrared detection is demonstrated in forward biased Ge (out to 240 μm), Si (220 μm) and InGaAs (90 μm) *p-i-n* with D^* up to 5×10^{10} cm Hz$<^{1/2}$/W at 4.2 K. For silicon detectors, this is the longest response wavelength ever reported. Estimates for the responsivity and the detectivity for unoptimized commercial samples are provided by comparison with a silicon composite bolometer. The variations observed in the long wavelength threshold (λ_t suggest that if correlations with device processing parameters can be successfully established, this approach can be used to tailor detectors for different IR wavelength regions. Spectral response comparison with a single *p-i* structure strongly supports the detection mechanism and opens the possibility of detector optimization using multilayered structures.

During recent years there has been growing interests in the possibility of fabricating infrared detectors for different spectral regions in a single semiconductor material other than $Hg_{1-x}Cd_xTe$. The material of choice for this purpose, on grounds of chemical stability and the advanced state of processing technology, is silicon;[1] although Ge, Si-Ge,[2,3] and the more refractory III-V compounds [4] are also promising candidates. The binding energies for available extrinsic dopants in Si and Ge have previously limited the spectral ranges for detection below about 30 and 115 μm, respectively. The range of Ge detectors has been extended to about 180 μ by applying a stress along the [10] axis.[5] Recently, however, Coon *et al.*[6] demonstrated an IR detection mechanism in forward biased *p-i-n* diodes that appears to allow tailoring of spectral response at very long wavelengths with easily fabricated devices.

As described earlier,[6] this photodetection relies on the formation of a work function energy barrier at the interface between lightly and heavily doped regions of a semiconductor. IR photons are absorbed in the p^+ or n^+ emitter region, and under forward bias the photoexcited carriers are emitted over the barrier by a process analogous to the photoelectric effect at a metal (photocathode)-vacuum interface. At lower doping levels normally used for photoconductive extrinsic IR detectors, the barrier height, and therefore the long wavelength IR threshold wavelength (λ_t), corresponds to the binding energy of the dopant impurity. As the doping concentration is increased and approaches the metal-insulator transition, the barrier height is lowered.[7] In fact, we expect that interfacial work functions could be made exceedingly small simply by increasing the *n* or *p* doping. In this letter we report the observation of spectral responses out to 240, 220, and 90 μm for Ge, Si, and $In_{0.47}Ga_{0.53}As$ samples, respectively. All the samples reported here are Fujitsu *p-i-n*structures unless noted otherwise. Spreading resistance probe data for representative devices indicate that carrier concentrations near the contact surfaces of the *p* and *n* regions can approach values of about $10^{20}/cm^3$. The variation in λ_t among different materials and between different Si samples with different impurity concentrations suggests that it will be possible, using controlled epitaxial growth methods, to fabricate devices based on this mechanism that are tailored to different spectral bands in the far infrared (FIR).

The samples were used as detectors in a Fourier transform spectroscopy (FTS) setup. A Michelson interferometer with a mercury arc source provides modulated IR radiation from 10 to 40 μm. The detector under test is mounted on the cold plate of a commercial liquid helium dewar[8] facing the interferometer output through a polyethylene vacuum window. Visible and 300 K near-IR radiation are filtered by two sheets of black polyethylene mounted on the cold plate with the detector. Background radiation is further reduced with a cooled parabolic light condenser that limits the detector field-of-view. A 10 MΩ load resistor and a JFET first stage amplifier are mounted close to the forward biased detector on the cold plate to reduce noise.

The raw spectrum that results from an FTS measurement is the product of the incident spectrum with the response curve of the sample. To extract the response curve, a silicon composite bolometer[8] was used as a reference detector. Both the bolometer and the sample under test were mounted on a rotatable wheel allowing either detector to be positioned at the exit of the light condenser while the dewar was cold. This arrangement ensures that both detectors see the same optical path. The setup also minimizes the time, and therefore the potential for drift, between data and reference measurements. The bolometer sensitivity was determined from *I-V* measurements made immediately before obtaining spectra. The response was assumed to be flat, so that dividing the bolometer signal spectrum by the sensitivity yields the incident power spectrum. The ratio of the sample photosignal spectrum to the incident power spectrum then produces the diode sensitivity.

Figure 1 shows raw spectra for a Ge sample with various detector biases. Radiation is detected out to 240 ± 20 μm with a bias of 0.87 V. With decreasing bias, λ_t moves to shorter wavelengths suggesting that barrier lowering occurs at high bias. An IR response with a threshold of ~40 μm could be seen down to a bias of 0.7 V which agrees well with the flatband voltage of 0.66 V for Ge.

The spectral response for another Ge sample (Fig. 2) shows a λ_t of 175 ± 10 μm. Even though this inexpensive

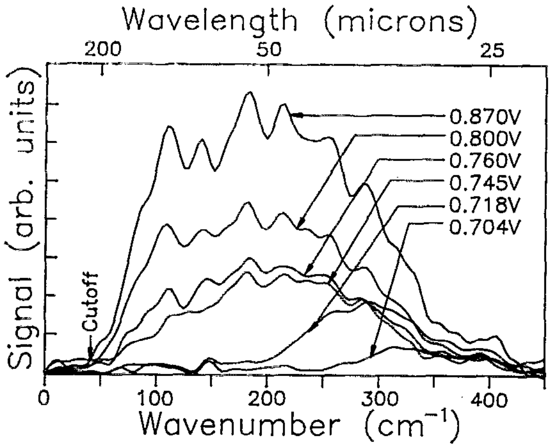

FIG. 1. Raw spectra obtained with a Ge sample at 4.2 K. the threshold at high bias corresponds to about 240±20 μm and shifts to shorter wavelengths as the bias is decreased. Also visible are Fabry–Perot oscillations superimposed as peaks and valleys on the raw data.

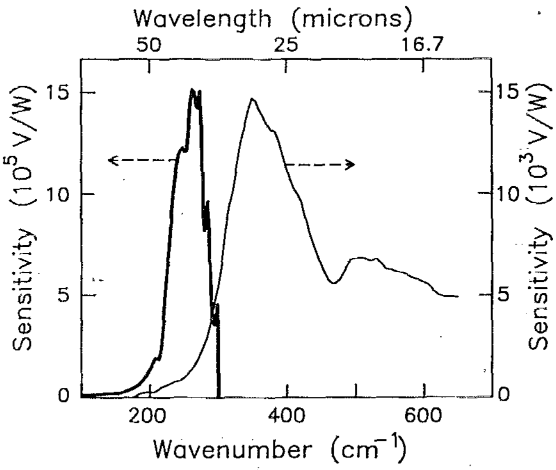

FIG. 3. The spectral response for a Si sample at 1.5 K with a bias voltage of 2V showing a λ_t of 57±2 μm and a peak response at 28 μm. The peak response was increased by 100 fold (dark line) when the incident radiation is limited to $\lambda > 33$ μm.

commercial diode has not been optimized, the performance is encouraging. The peak sensitivity of 1.4×10^5 V/W occurs at a frequency of about 95 cm^{-1}. The NEP at that frequency is 1×10^{-11} W/$\sqrt{\text{Hz}}$ and $D^*=3\times 10^{10}$ cm Hz$^{1/2}$ W^{-1}. $D^*=5\times 10^{10}$ cm Hz$^{1/2}$ W^{-1} for the bolometer with similar background illumination. When the input IR bandwidth is decreased by using a SrF_2 filter, which cuts off wavelengths $\leqslant$ 40 μm, the peak responsivity increases to 1.9×10^5V/W with λ_t=200±10 μm. This indicates a limited number of carriers for photoexcitation which suggests that only the carriers very close to the interface might be useful in the detection process. This supports the idea of having multilayers with thin regions for optimization.

Figure 3 shows a Si response curve similar to that of Ge, except that λ_t is at 57±2 μm. The peak sensitivity at ~30 μm for this Si sample with a 2.0 V bias is 1.5×10^4 V/W at 350 cm^{-1}. The NEP is 8×10^{-11} W/$\sqrt{\text{Hz}}$ and $D^*=6\times 10^9$ cm Hz$^{1/2}$ W^{-1}. As the incident bandwidth was narrowed the response increases and D^* becomes 5×10^{10} cm Hz$^{1/2}$ W^{-1}. As seen in Fig. 4(a), a different Si sample shows a λ_t near 220 μm at 1.5 K with a bias of 2.3 V. Figure 4 also shows both the intensity and bias dependence of the raw spectra. Earlier work[6] suggested that the photocurrent (I) was related to the detector bias by the equation $I=G(V\times V_0)$, where V and V_0 are the detector and the flatband voltage, respectively. The inset demonstrates that the proportionality constant G is linearly dependent on intensity.

Also studied was the bias dependence of the raw spec-

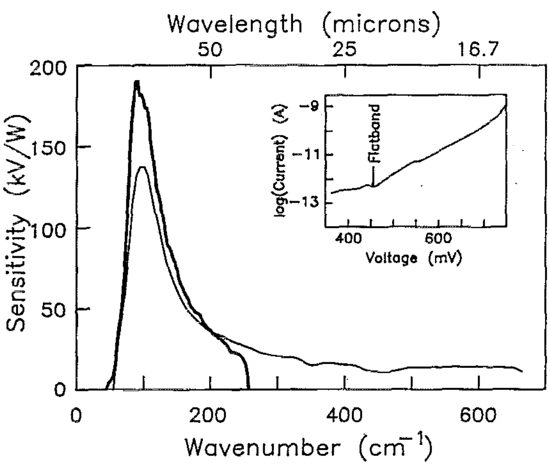

FIG. 2. The spectral response of a Ge sample at 1.5 K with a detector voltage of 0.7 V showing λ_t=175±10 μm with $\Delta\lambda > 70$ μ (response bandwidth corresponds to half height points). The dark line corresponds to the response when a longpass (cut on 40 μ, SrF_2/diamond powder) filter was placed on the light path to reduce the incident bandwidth. The sensitivity is obtained by dividing the raw data by the bolometer spectrum. The inset shows the dark I-V curve with a flatband voltage around 0.46 V.

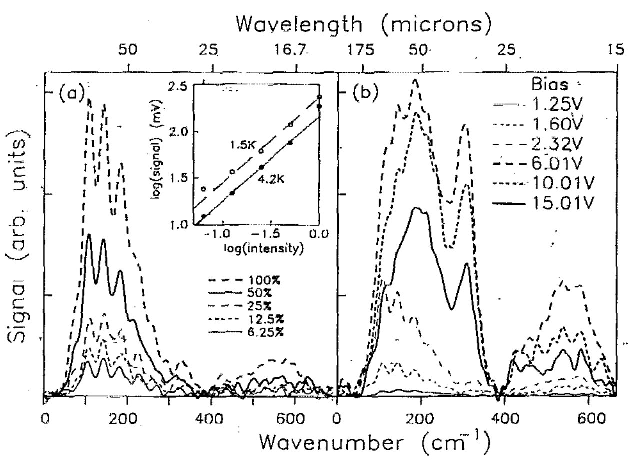

FIG. 4. (a) The intensity dependence of the raw spectral data at 1.5 K for a Si sample forward biased with 2.3 V. The curves are labelled according to the intensity as a percent of maximum incident intensity. The inset shows the photocurrent signal vs intensity plot indicating almost linear dependence. (b) The bias dependence of the raw data at 1.5 K for the same detector. The response increases with bias up to about 6.0 V with a $\Delta\lambda \geqslant 70$μm and then decreases. The dip around 25 μm is due to a beam splitter minimum.

tra for this particular Si diode at 1.5 K. As expected, IR photons were detected above a bias voltage of 1.1 V, flat-band voltage for Si. (See Fig. 4.) The response initially increases with increasing bias and then decreases. As the bias is increased, one would expect and increase in the response due to the impact ionization gain. Also the increase in λ_t will increase the response by allowing carriers to be collected more efficiently since they could sustain more collisions due to the lower energy required to overcome the barrier. This will allow the carriers which are further away from the junction to be collected and contribute to the photocurrent. However, our data not only show an increase with increasing bias up to 6 V [See Fig. 4(b)] but also a decrease with a further increase in bias beyond 6 V. Even though this needs further evaluation one might speculate that with increased impact ionization, an increased amount of ionized impurities can act as traps which could recombine the carriers to decrease the response.

The raw spectral data for an RCA InGAAs sample showed a λ_t of 90 μm and a strong dip near 40 μm which may be due to bulk absorption. This sample had the poorest performance of those tested. The peak sensitivity was only about 900 V/W at 400 cm^{-1} with an NEP of $1.4 \times 10^{-8} W/\sqrt{Hz}$ and D^* of 7×10^7 cm $Hz^{1/2}$ W^{-1}.

As indicated in our previous study,[6] the IR response of these *p-i-n* structures arises from photoexcitation of both holes and electrons at the biased junctions. In order to confirm the mechanism and as a preliminary feasibility step towards fabricating higher performance multilayered *p-i-p-i-*... or *n-i-n-i-*... structures a simple test was carried out using Silicon Detector Corporation (SDC-150) *p-i-n* structures which consist of about 100 μm *i*-regions and about 1 μm *p* and *n* regions. Two samples were selected from the same batch and the *n* layer was etched from one of the samples leaving only a *p-i* interface. A back contact to the *i*-region was then made by polishing (introducing defects) and Al evaporation. Since both boron and phosphorus have about the same impurity level energy in silicon (45 meV) and have similar concentrations in the samples, both structures should have a similar λ_t. The raw spectral data shown in Fig. 5 demonstrate that this is the case. The *p-i* spectrum in the figure shows a higher response than the *p-i-n* structure because of a significantly higher detector bias. Peak D^* for the two samples was $\sim 2 \times 10^9$ and 6×10^8 cm $Hz^{1/2}W^{-1}$, respectively. A direct comparison of spectra at the same detector bias was not possible because the voltage limits on the commercial cryostat feedthroughs restricted accessible biases for the lower impedance *p-i-n* structure to values where the *p-i-* structure showed little response. However, the plot of the peak IR signal response versus detector voltage shown in the inset in Fig. 5 demonstrates that the *p-i-n* structure has a higher response than the *p-i-* structure at a given bias. The preliminary indications are that both the electrons and holes contribute significantly. Although a higher impurity concentration can be achieved using *p*-type impurities (in Si MBE fabrication),[9] higher operational temperatures have been obtained[1] for extrinsic detectors with donor impurities in Si.

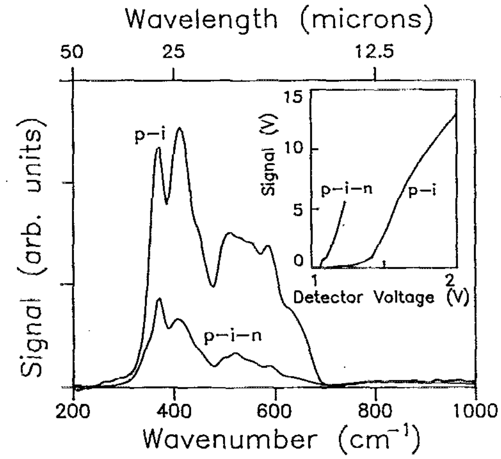

FIG. 5. Raw data for silicon *p-i-n* (SDC-150) and *p-i-* structures at 4.2 K obtained with 1.2 and 2.0 V, bias across the sample, respectively. λ_t for both structures is 35 ± 3 μm. The inset shows the signal detected for both structures vs the detector bias voltage.

Hence a detailed study would be needed to determine whether the acceptor or donor impurities would be more advantageous, which can also depend on detector requirements.

In conclusion, we have confirmed that commercially fabricated *p-i-n* diodes in Ge, Si and InGaAs are capable of exhibiting broadband far-infrared response under forward bias, with λ_t's which ar voltage tunable. Spectral response measurements indicate that this latter effect is due to bias induced lowering of the interfacial work function barrier between the highly doped emitter and intrinsic regions. In the case of Si devices a detectivity of 5×10^{10} cm $Hz/^{1/2}/W$ has been measured at 1.5 K corresponding to a $\lambda_t$of 57 μm. Our results suggest that with proper control of junction growth and doping, e.g., by MBE techniques, it should be possible to fabricate in a single semiconductor material high sensitivity detectors that are tailored to a wide variety of spectral bands extending into the far infrared.

This work was supported in part by the U.S. NSF under grant No. ECS 9006078. The authors wish to thank H. K. Kim for allowing us to use his semiconductor parameter analyzer, Y. F. Lin for making the contact, and the referee for his careful review and comments.

[1] N. Sclar, Progress in Quantum Electronics (Pergamon Press, New York, 1984), Vol. 9, pp. 149–257.
[2] T. L. Lin and J. Maserjian, Appl. Phys. Lett. **59**, 14 (1990).
[3] R. P. G. Karunasiri, J. S. Park, Y. J. Mii, and K. L. Wang, Appl. Phys. Lett. **57**, 2585 (1990).
[4] D. D. Coon, J. Vac. Sci. Technol. A **8**, 2950 (1990).
[5] E. E. Haller, M. R. Hueschen, and P. L. Richards, Appl. Phys. Lett. **34**, 495 (1978).
[6] D. D. Coon, R. P. Devaty, A. G. U. Perera, and R. E. Sherriff, Appl. Phys. Lett. **55**, 1738 (1989).
[7] J. Wagner and J. A. del Alamo, J. Appl. Phys. **63**, 425 (1988).
[8] A. W. Davidson, Company Literature-Infrared Laboratories, Inc. 1808 E. 17th St. Tucson AZ 85719.
[9] R. W.Fathauer (private communication).