Far-infrared free-hole absorption in epitaxial silicon films for homojunction detectors

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We report on the investigation of free-carrier absorption characteristics for epitaxially grown p-type silicon thin films in the far-infrared region (50–200 μm), where Si homojunction interfacial workfunction internal photoemission (HIWIP) detectors are employed. Five Si thin films were grown by molecular beam epitaxy on different silicon substrates over a range of carrier concentrations, and the experimental absorption data were compared with calculated results. The free-hole absorption is found to be almost independent of the measured wavelength. A linear regression relationship between the absorption coefficient and the carrier concentration, in agreement with theory, has been obtained and employed to calculate the photon absorption probability in HIWIP detectors. © *1997 American Institute of Physics.* [S0003-6951(97)04130-2]

Recently, considerable interest has arisen in the development of internal photoemission semiconductor-junction infrared (IR) detectors.[1–3] The concept of internal photoemission was employed in homojunction structures for far-infrared (FIR) detection and was classified[4] as homojunction interfacial work-function internal photoemission (HIWIP) detection.[3–5] Such detectors are suitable for space astronomy applications at wavelengths greater than 50 μm.[3] The operation of the HIWIP detector is based on the internal photoemission occurring at the interface between a heavily doped absorber/emitter layer and an intrinsic layer. Recent modeling studies[3] have shown that Si HIWIP FIR detectors could have a performance comparable to that of conventional Ge FIR photoconductors[6] or Ge blocked-impurity-band (BIB) FIR detectors,[7] with unique material advantages. The detection mechanism of HIWIP detectors involves FIR free carrier absorption in the highly-doped thin emitter layers, followed by the internal photoemission of barrier penetration and collection. Hence, it is important to understand the FIR-free carrier absorption behavior in silicon thin films, both for fundamental as well as device performance reasons.

Previous studies of optical absorption in silicon were limited to relatively short wavelengths ($\leqslant$40 μm).[8] No free-carrier absorption data are available for the wavelength range $\geqslant$50 μm, where the HIWIP FIR detectors usually work. In this letter, free-carrier absorption in p-type Si thin films with concentrations in the range of 10^{17} to 10^{19} cm^{-3} was both experimentally and theoretically investigated, in the FIR region (50–200 μm), in order to design and optimize HIWIP FIR detectors.

Five p-type silicon thin films were grown by molecular beam epitaxy (MBE) on pieces from two different silicon (100) wafers. The entire structure was capped by a 10 nm undoped layer to protect the surface. The carrier concentrations and mobilities in the films are extracted from Hall effect measurements, while the epilayer thicknesses are obtained by profilometer thickness measurements. Details of these samples are listed in Table I. The mobilities of our samples are close to the high dopant level[9] average value of 50 cm^2/Vs. To determine the infrared absorption of the samples, the transmission and reflectance were measured using a Perkin-Elmer, system 2000, Fourier transform infrared spectrometer (FTIR) and a Si composite bolometer detector. The measurements were performed at room temperature with a resolution of 2 cm^{-1} and no changes are expected at low temperatures, as described below. Both the transmission and reflectance measurements were made using a normal incidence geometry with light incident on the doped layer surface. A 2.5 μm Mylar Pellicle film was used as a beamsplitter by placing it at 45° with the incident light in the reflectance measurements. The substrates were polished in order to reduce the energy losses.

The absorption (A) in thin films is determined from the transmission (T) and reflection (R) in conjunction with the expression

$$A = 1 - T - R \tag{1}$$

and further subtraction of the absorption of the substrates. The absorption results of two typical thin films over the wavelength range from 50 to 200 μm are shown in Fig. 1. The experimental curves have been smoothed using the

TABLE I. Characteristics of Si thin film samples examined in this study. Substrate wafer 1 is with thickness of 475 μm, resistivity of 31.4 Ω cm and concentration of 1.31×10^{14} cm^{-3}. Substrate wafer 2 is with thickness of 480 μm, resistivity of 33.0 Ω cm and concentration of 1.20×10^{14} cm^{-3}. Boron was used to dope all doped layers.

Sample	Substrate	Thickness (μm)	Doping concentration P (cm^{-3})	Mobility μ (cm^2/Vs)
MT324F	wafer 2	0.68	5.5×10^{19}	29
MT325F	wafer 1	0.73	1.5×10^{19}	42
MT326F	wafer 1	1.37	7.1×10^{18}	55
MT327F	wafer 1	2.46	1.9×10^{18}	110
MT328F	wafer 2	2.42	8.1×10^{17}	126

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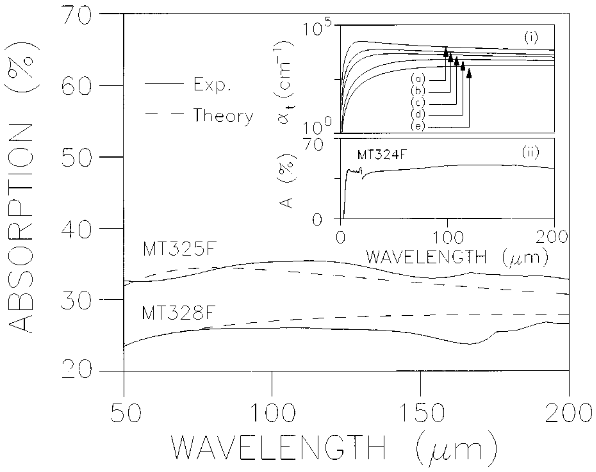

FIG. 1. Experimental FIR free hole absorption in two p-Si thin films (MT325F and MT328F) at room temperature (solid curves). The dashed curves are the theoretical results without any fitting parameters. The inset (i) shows the calculated free carrier absorption coefficient (α_t) using the parameters in Table I of five samples (a) MT324F, (b) MT325F, (c) MT326F, (d) MT327F, and (e) MT328F in a wavelength range from 1 to 200 μm, and the inset (ii) shows the experimental absorption (A) of sample MT324F in the same range using two detectors; HgCdTe (2–20 μm) and Si bolometer (20–200 μm), displaying the wavelength square dependence at shorter wavelengths.

FTIR software. The theoretical absorption curves shown in Fig. 1 were calculated from the complex dielectric constant of the Si layer by matching electric and magnetic fields at the interfaces.[10] The dielectric constant of the thin films is derived from the frequency-dependent conductivity for free carriers by

$$\sigma = \frac{\sigma_0}{1 - i\omega\tau} \tag{2}$$

where σ_0 is the dc conductivity and τ is the relaxation time, which is independent of frequency ω in the semiclassical transport theory. Since our main interest is in the FIR range ($\geqslant$50 μm), the other contributions, e.g., intervalence band transitions and lattice vibrations, have been ignored. Using the measured values of mobility μ in Table I, the relaxation time was determined by the relation $\mu = e\tau/m_p^*$, where $m_p^* = 0.37m_0$[8] is the heavy-hole effective mass in Si, m_0 is the free-electron mass, and e is the magnitude of the electron charge. This means that no free parameters are used to fit the experimental data with the modeling results.

The reasonably good agreement between the experimental and theoretical results strongly demonstrates that the absorption is actually due to the contribution of free carriers. Further evidence for the identification of free-carrier absorption in these thin films can clearly be seen from the absorption of their substrates, where our experiments show that their absorption can generally be neglected [the absorption coefficient is in the order of 10^{-2} cm^{-1}, in comparison with the order of 10^3–10^4 cm^{-1} in thin films (see below)]. The measured values of absorption in the films were found to be almost independent of wavelength, which is similar to the results for Schottky barrier IR detector samples beyond the lattice bands,[11] SiGe layers above 15 μm,[2] and GaAs thin films above 50 μm.[12] The other three samples measured displayed the same absorption features. Measurements also show that the free-carrier absorption increases with increasing doping concentration. This is expected as the free carrier absorption is proportional to both the carrier concentration and scattering rate (also increases with doping).

The absorption depends not only on the real part of the refractive index, but also on its imaginary part, which is proportional to the absorption coefficient (α) defined by

$$\alpha = 2kq \tag{3}$$

where k is the imaginary part of the refractive index, and q is the wave number of the incident radiation. In experiments, the absorption coefficient α of the thin films can be obtained from

$$\alpha = \frac{1}{d}\ln\left(\frac{1-R}{T}\right) \tag{4}$$

where d is the layer thickness. In contrast to the wavelength squared dependence of the free carrier absorption coefficient for shorter wavelengths,[8] the measured free-carrier absorption coefficients for the five thin films are almost independent of the FIR (50–200 μm) wavelength. To explain this, the free-carrier absorption of five Si thin films in a wide wavelength range (1–200 μm) has been calculated by the model described above, as shown in inset (i) of Fig. 1. It is seen that, at shorter wavelengths (1–20–40 μm), the absorption coefficient increases as the wavelength squared, and at longer wavelengths is almost independent of the wavelength. Since free-carrier absorption is an indirect transition process involving the light absorption and quasi-particle interaction (such as phonons, defects, and lattice imperfections) by free carriers,[13] the weak energy of photons in the FIR region results in a reduced excitation of carriers to higher energy levels within the same energy valley. The samples were also measured in the 2–20 μm range by use of a HgCdTe detector with one sample displayed in inset (ii) of Fig. 1, which shows near wavelength squared dependence of the free-carrier absorption and coincides with the longer wavelength results by the Si bolometer detector, in good agreement with the theory shown in inset (i). The above arguments strongly demonstrate the reliability of both the modeling and experimental results.

The most important result in connection with the HIWIP detector is the relationship between the free-carrier absorption coefficient and the carrier concentration. The strength of the free-hole absorption at the wavelength of 80 μm, obtained from both the measurements and calculation, is shown in Fig. 2. Both show that the absorption can be well described by a linear relation between the absorption coefficient and the concentration of holes, in accordance with the case for shorter wavelengths[8]. The fitted regression formulas as a function of hole concentration (P) below 10^{20} cm^{-3} are for the modeling:

$$\alpha_t = 2.06\times 10^{-16}\text{cm}^2 * P \tag{5}$$

and for experiment

$$\alpha_d = 3.71\times 10^{-16}\text{cm}^2 * P \tag{6}$$

which are close to the classical expressions[8] at wavelengths $\lambda = 20$–40 μm. We can see that the theoretical calculation is

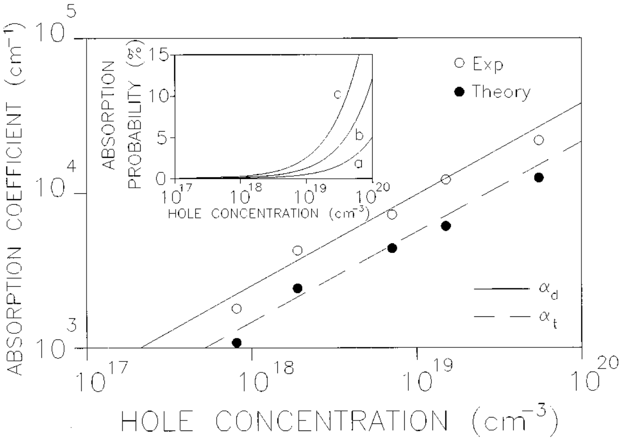

FIG. 2. Experimental (open circles) and theoretical (solid circles) FIR free hole absorption coefficient as a function of hole concentration at 80 μm. Both show a linear relation between α and hole concentration (solid line for experiments α_d and dashed line for theory α_t). The inset shows the calculated photon absorption probability in relation with the emitter layer concentration in a Si HIWIP FIR detector with the emitter layer thickness of (a) 100, (b) 250, and (c) 500 Å and bottom layer concentration of 2×10^{19} cm^{-3} and a thickness of 6000 Å.

in reasonable agreement with the experimental results. This level of agreement is also observed in the shorter wavelength case, where it is also seen that the experimental absorption coefficient is larger, by a factor of 1.7, than the theoretical value mainly due to the relative simplification of the theory.[8]

A high absorption coefficient (10^3–10^4 cm^{-1}) in the FIR range is an important advantage for HIWIP detectors, since the absorption coefficient is almost independent of temperature due to the almost invariant carrier concentration and mobility with temperature. The total quantum efficiency of a HIWIP detector is the product of photon absorption probability, internal quantum efficiency, and barrier collection efficiency.[4] The photon absorption probability for HIWIP detectors can be calculated as[4]

$$\eta_a=\{1+\exp[-(\alpha_e W_e+2\alpha_b W_b)]\}[1-\exp(-\alpha_e W_e)] \tag{7}$$

where α_e, α_b are the free-carrier absorption coefficients in the emitter layer (thickness W_e) and the bottom contact layer (thickness W_b), respectively. By using the experimental relationship in Eq. (6) and the layer thicknesses, the photon absorption probability was calculated for HIWIP detectors as a function of carrier concentration, which is shown in the inset of Fig. 2. Apart from the increase of absorption probability due to the increase of hole absorption in thicker emitter layers, it can be seen that the photon absorption probability increases rapidly when the carrier concentration increases from $\sim10^{19}$ to 10^{20} cm^{-3}. The collection efficiency also depends on the diffusion length, however, the effect is much weaker compared with the effect of absorption probability as seen from the mobility data. Therefore, this strong enhancement of the photon absorption probability with the carrier concentration shows that highly doped emitter layers are more attractive for higher quantum efficiency in HIWIP detectors, which has been demonstrated in our recent GaAs HIWIP experimental results.[5] In addition, it was shown,[4] from the high density theory, that only a small increase in the emitter layer concentration (around 10^{19}–10^{20} cm^{-3}) can cause a large increase in the cutoff wavelength of the detectors. Therefore, higher performance and longer cutoff wavelength HIWIP detectors can be obtained in this concentration range.

In summary, the free-carrier absorption in p-type Si thin films grown by MBE in the far-infrared region (50–200 μm) was investigated, which is the range of interest for HIWIP detectors. Both the calculations and experimental data reveal that the hole absorption is almost independent of wavelength. The theoretical results also confirm the wavelength squared dependence of the absorption coefficient at shorter wavelengths, which agrees with the previous experimental results. A linear regression relationship between the absorption coefficient and carrier concentration was obtained, which is essential for the performance of HIWIP detectors.

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