Observation of submillimeter radiation from a nonequilibrium electron–hole plasma in silicon at 4.2 K

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Experiments have revealed an intense generation of submillimeter radiation ($\lambda \simeq 80$–$120\ \mu$m) from a nonequilibrium electron–hole plasma in silicon in an electric field at liquid-helium temperatures. The experimental results are reported. Mechanisms for the emission are discussed.

The existing active sources of submillimeter radiation which utilize an inverted distribution of hot charge carriers operate at liquid-helium temperatures and in strong fields E and H (Ref. 1). It would thus be desirable to achieve stimulated submillimeter emission in hot-carrier systems at $T \leqslant 77$ K without using magnetic fields. The possibility of generating submillimeter radiation in the promising semiconductor Si, in which the energy of an optical phonon is $\hbar\omega_0 = 735$ K, has not been realized because of difficulties stemming from the large ionization energy of impurities at liquid-helium temperatures.[1] Generation of submillimeter radiation in the wavelength region $\lambda \simeq 200$–$350\ \mu$m has recently been observed in experiments on p-Si at $T = 77$ K in strong fields $\mathbf{E} \perp \mathbf{H}$. The investigators explained the inversion mechanism in terms of a quantization of the spectrum of light holes in a magnetic field and an intersubband tunneling of hot holes. However, the need to use strong fields E and H ($H \simeq$ 20–25 kOe) suggests that this effect will not find much practical use.

The present experiments were carried out at $T = 4.2$ K on n-Si⟨P⟩ samples which were rectangular parallelepipeds with dimensions of $1.5 \times 2.2 \times 22.5$ mm with [111], $[1\bar{1}0]$, and [112] orientations, respectively. The dopant concentration was $N_D - N_A \simeq 8 \times 10^{12}$ cm^{-3}. The test samples had a "short" geometry. Ohmic contacts were applied to the 22.5×1.5 mm^2 faces, which were perpendicular to the [111] direction. Figure 1 shows the experimental layout and the directions of the electric field and the photoexcitation with respect to the crystallographic axes of the test sample. The sample, the photoexcitation source, and the photodetector, with a system of filters, were immersed directly in liquid helium. This measure prevented background electromagnetic radiation from reaching the test sample. The photoexcitation of the carriers was carried out continuously and also in 20-μs pulses from a source of monochromatic radiation based on GaAs IR diodes with a photon energy $\hbar\omega > \mathscr{E}_q^{\mathrm{Si}}$. The photoexcitation intensity corresponded to a maximum value $\sim 5 \times 10^{14}$ cm^{-3} for the concentration of the electron–hole pairs which were generated. The distribution of excitons over the volume was assumed to be uniform. The basis for this assumption is that, although the carriers are generated by the light in only a thin surface layer, the large diffusion coefficient[3] allows them to uniformly fill the test sample, ~ 1.5 mm thick, over a time $\sim 10^{-6}$ s. During the pulsed photoex-

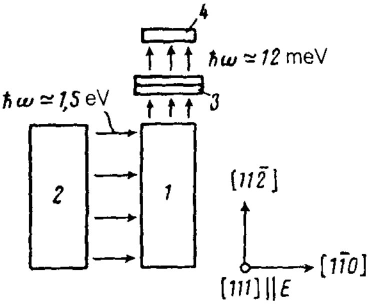

FIG. 1. Experimental layout and crystallographic orientation of the sample. *1*—The Si⟨P⟩ test sample; *2*—photoexcitation source (GaAs); *3*—filters; *4*—Ge⟨Ga⟩ photodetector.

citation, at a frequency of 3 Hz, electric field pulses were applied to the sample in a synchronous fashion under voltage-generator conditions. These field pulses ranged in length up to 10 μs. They were applied 0–50 μs after the photoexcitation pulses.

The radiation from the sample during the electric field pulse was detected by a Ge⟨Ga⟩ photodetector. The spectral region of sensitivity of the photodetector, along with its system of filters (consisting of a fluoroplastic and black polyethylene, cooled to $T=4.2$ K), is $\lambda \simeq 80$–120 μm, with a peak at $\lambda = 100$ μm.

Figure 2 shows the radiation intensity versus the electric field, $I(E)$, along with current-voltage characteristics recorded 5.0 μs after the end of the photoexcitation pulse.

When a pulse of an electric field $E \geqslant 300$ V/cm is applied, excitons undergo dissociation. The threshold field for exciton breakdown, E_c, and the concentration of free carriers depend on the photoexcitation intensity only when this intensity is low. As the photoexcitation intensity increases, the threshold E_c and the carrier concentration in the electron–hole plasma become independent of the electric field. Evidence that the excitons undergo ionization in the electric field comes from the circumstance

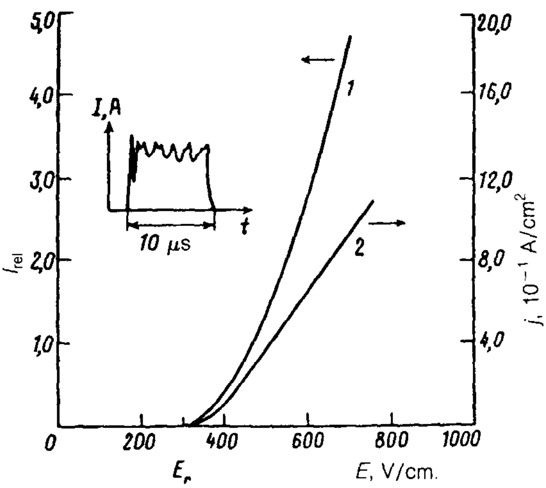

FIG. 2. *1*—Intensity of the submillimeter radiation versus the electric field; *2*—current-voltage characteristic of the sample at $T = 4.2$ K. Here E_c is the threshold electric field for breakdown of excitons.

that the carrier concentration in the region of full ionization is much higher than the concentration of impurity centers in the sample. Further evidence comes from the low voltage at which breakdown begins. The activation energy for the phosphorus impurity centers in silicon is $E_i \simeq 45$ meV. The breakdown voltage of the impurity centers also depends on the impurity concentration. In an experiment without photoexcitation, with pulsed electric fields up to $E \simeq 1500$ V/cm , we did not observe impurity breakdown. The maximum delay of the field pulse with respect to the photoexcitation pulse at which exciton breakdown was still possible ranged from 300 to 600 μs. With increasing delay, the breakdown electric field increases, while the peak intensities of the submillimeter radiation and of the current through the sample decrease.

That electric breakdown of excitons is possible at such long delays of the field pulse with respect to the photoexcitation pulse seems contradictory, since the exciton lifetimes in pure silicon crystals ($N_i < 10^{11}$ cm^{-3}) are 2–5 μs, according to the kinetics of luminescence decay (Ref. 4, for example). However, the observed effect could be explained in terms of the existence of bound excitons or of excited states and complexes including H^--like centers, whose lifetimes at liquid-helium temperatures are tens of microseconds,[5] according to measurements of photoconductivity decay.

The inset in Fig. 2 is a typical oscilloscope trace of the current through the sample at $E > E_c$. The observed instability of the current in the sample at $E > E_c$ is of independent interest. The average frequency (~ 1 MHz) of the irregular current oscillations depends on the electric field. The modulation amounts to $\sim 50\%$ of the peak value of the current. The instability can be explained in terms of an exclusion of nonequilibrium carriers, which results in a stratification of the electron–hole plasma and the onset of spatial variations in the carrier concentrations in the sample. Preliminary experiments showed that this instability model, developed in Ref. 6, is the closest to the truth. A distinctive feature of the submillimeter radiation which was observed is that its intensity depends on the amplitude of the current through the sample; i.e., the radiation intensity has a modulation similar to that of the current.

The integrated intensity of this radiation is far higher than that of the spontaneous submillimeter emission in p-Ge, which stems from interband inversion of hot holes in fields $\mathbf{E} \perp \mathbf{H}$. This conclusion is based on an experimental study and a calculation of the intensity of the spontaneous emission per hole, $I^{lh}_{\text{Ge}} N^{-1}_{\text{Ge}}$, in p-Ge with a dopant concentration $N_{\text{Ge}} = N_{\text{A}} - N_{\text{D}} = 10^{14}$ cm^{-3} for a sample in the crystallographic orientation $\mathbf{E} \| [110] \perp \mathbf{H} \| [111]$ ($E = 500$ V/cm, $H = 5.5$ kOe) in the wavelength region $\lambda \simeq 80$–120 μm. This comparative estimate yields

$$\frac{I_{\text{Si}} N^{-1}_{\text{Si}}}{2 I^{lh}_{\text{Ge}} N^{-1}_{\text{Ge}}} > 1,$$

where I_{Si} is the intensity of the spontaneous emission of Si, and N_{Si} is the concentration of carriers (electron and holes) in Si.

The submillimeter emission from the nonequilibrium electron–hole plasma in Si may result from several mechanisms: direct optical transitions of hot carriers between the subbands of light and heavy holes, I^{lh}; exciton emission, I^{exc} (since the binding energy of indirect excitons in Si, $\hbar\omega_{\text{exc}} \simeq 10$–$14$ meV, lies in the photosensitivity spectral region of p-Ge⟨Ga⟩); "Drude" emission of electrons and holes, I^{ll} and I^{hh}; and emission from the crystal lattice due to its heating, I^T:

$$I^{\text{tot}} = I^{lh} + I^{\text{exc}} + I^{ll} + I^{hh} + I^{T} \simeq I^{lh} + I^{\text{exc}}.$$

A study was carried out to determine the roles played by these mechanisms in the intensity of the submillimeter emission. The results of an experiment on the submillimeter emission by equilibrium electrons and holes after the electric field pulse and also an estimate of the intensity of the Drude emission show that these factors are negligible.

A nonequilibrium emission due to direct optical transitions between the subbands of light and heavy holes, $l \to h$, in Si was discussed theoretically in Ref. 1. It was not observed in an experiment[2] on p-Si. An alternative mechanism for the increase in the $l \to h$ emission in a nonequilibrium electron–hole plasma might involve Coulomb scattering of fast electrons by heavy holes resulting in the conversion of the latter into light holes. This scattering mechanism is effective for electrons with energies $\mathscr{E}_e > (m_{\text{h}}/m_{\text{e}})kT$, where m_{h} and m_{e} are the effective masses of the holes and electrons, respectively. At high hole concentrations this mechanism for a "pumping" of heavy holes into the light subband might become dominant.[7] To determine the role played by this mechanism in the emission, we studied some samples in a different crystallographic orientation. In the configuration $\mathbf{E} \| [100]$, there should be a change in the extent to which heavy holes are pumped into the light subband and a corresponding change in the emission intensity, because of the change in the ratio $m_{\text{h}}/m_{\text{e}}$ in the direction in which the electric field is applied. In practice, however, we observed no change in the emission intensity due to the change in the orientation of the electric field.

The primary mechanism for the submillimeter radiation is most probably the emission of photons $\hbar\omega_{\text{exc}}$ upon the transition of free carriers to exciton levels. Evidence for this conclusion comes from the binding energies of excitons in Si which have been determined from measurements of absorption and emission spectra. These energies are in the interval $\hbar\omega_{\text{exc}} \simeq 10$–$14$ meV. There are three most intense lines, with energies of 10.2, 11.4, and 12.0 meV. This region is in the photosensitivity spectral region of the Ge⟨Ga⟩ photodetector which we used. Further evidence in favor of this mechanism comes from the large effective cross section for the binding of an electron and a hole into an exciton at liquid-helium temperatures.

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