

Features of plasma reflection of strongly doped Si(Li)

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A fine structure was observed in the spectra of the plasma reflection in strongly doped Si(Li). This indicates the existence of an electron-ion "condensate" with concentrations 2×10^{20} and $1 \times 10^{20} \text{ cm}^{-3}$.

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In an investigation of the kinetics of the decay of a solid solution of Li in Si, under strong-doping conditions ($N_{Li} \geq 2 \times 10^{19} \text{ cm}^{-3}$), we had observed unusual time variations of the Hall concentration n_H and of the Hall mobility μ_H of the electrons.^[1] These singularities were explained within the framework of the model of electron-ion "condensation" and formation of a spatially-inhomogeneous distribution of electrically active Li ions. In other words, it was assumed that an additional energy minimum (metastable with respect to precipitation) exists for the ion-ion subsystem, and a "liquid" phase is formed in which the concentration of the free carriers (and of the Li ions) is $\sim (2-3) \times 10^{20} \text{ cm}^{-3}$. The quantitative estimates presented in that reference have confirmed that such a phase transition can exist.

In this communication we report the results of an investigation of plasma infrared reflection in Si(Li) crystals. The position of the plasma minimum in the reflection spectrum $R(\lambda)$ (λ is the wavelength of the incident light), as is well known, characterizes the concentration of the free carriers (see, e.g.,^[2]). In the case of a heterogeneous system, there should exist two (or more) minima corresponding to regions with different electron densities.

The samples were prepared from high-resistance dislocation-free *n*-Si. After implanting the Li at a temperature $T = 950-1100^\circ\text{C}$ and abrupt quenching to room temperature, the sample was ground and polished at $T \approx 0^\circ\text{C}$. The optical measurements were performed in a vacuum cryostat at temperatures $T = 90-300^\circ\text{K}$. All the preparatory operations (from quenching to measurements) consumed not more than 20-30 minutes. The accuracy with which the reflection coefficient R was measured was not lower than 0.2%.

Figure 1 shows typical spectra of $R(\lambda)$ in the range $\lambda = 2-6 \mu$ for samples with different concentrations n_H . In addition to the overall decrease of the reflection coefficient with increasing λ (with a minimum in the region $6.5-9 \mu$), an additional minimum is seen in the 3.8μ region, the depth of which exceeds by $\sim 5-10$ times the accuracy of the measuring apparatus. We note, first, that the position of the minimum is independent of n_H and, second, that there is no minimum at $n_H \leq 1.3 \times 10^{19} \text{ cm}^{-3}$. Assuming the effective electron mass to be $m = 0.26m_0$, we obtain for the concentration corresponding to $\lambda = 3.8 \mu$ the value $n_0 = 2 \times 10^{20} \text{ cm}^{-3}$.

We note further that no correlation exists between the depth of the overall decrease of $R(\lambda)$ and the parameter n_H (this correlation is distinctly observed in spatially

homogeneous regions). As a rule, this depth corresponded in our case to free-electron concentrations smaller than n_H . All these facts point to a strong spatial inhomogeneity of the investigated samples and a strongly fixed concentration in the highly doped regions.

With increasing experimental temperature to 230°K (at which the Li ions are still practically immobile), a noticeable broadening of the minimum is observed. This indicates that an appreciable contribution is made by acoustic scattering to the relaxation time τ , since the intensity of the impurity scattering for *n*-Si in the region $N_0 \sim 10^{20} \text{ cm}^{-3}$ and in the range $T = 90-230^\circ\text{K}$ does not depend on the temperature (see, e.g.,^[3]).

The calculated curves 5, 6, and 7 (which agree well with experiment) were obtained for the case $N_{Li} = n_0 = 2 \times 10^{20} \text{ cm}^{-3}$ and at a concentration $n_m = 2.0 \times 10^{19} \text{ cm}^{-3}$ in the interdrop medium. For the intradrop medium, the values of $\omega_p \tau$ [$\omega_p = (4\pi n_0 e^2 / m x_0)^{1/2}$ where x_0 is the dielectric constant of the crystal without the free carriers] were assumed to be respectively 50, 25, and 10. A comparison of the calculated and experimental curves has led to the conclusion that electron mobilities in the regions with $n_0 = 2 \times 10^{20} \text{ cm}^{-3}$ are $r_0 = 340 \text{ cm}^2/\text{V-sec}$ and $r_0 = 140 \text{ cm}^2/\text{V-sec}$ at $T = 90^\circ\text{K}$ and $T = 230^\circ\text{K}$, respectively. Such a high mobility (usually $r \approx 80 \text{ cm}^2/$

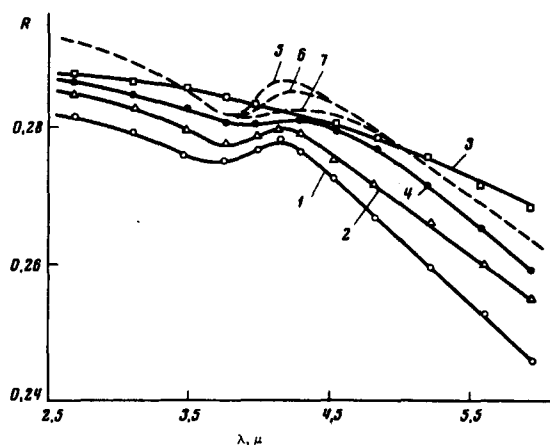


FIG. 1. Spectra of infrared reflection in Si(Li) as a function of the Hall concentration n_H and the measurement temperature T : 1, 2, 3— $T = 90^\circ\text{K}$, $n_H = 6 \times 10^{19}$, 4×10^{19} , and $1.3 \times 10^{19} \text{ cm}^{-3}$; 4— $T = 230^\circ\text{K}$, $n_H = 4 \times 10^{19} \text{ cm}^{-3}$; 5, 6, 7—theoretical curves calculated for an interdrop concentration $2 \times 10^{19} \text{ cm}^{-3}$ and an intradrop medium $2 \times 10^{20} \text{ cm}^{-3}$ at a relative fraction 1% of the light reflected from the drops, as a function of the parameter $\omega_p \tau = 50, 25, \text{ and } 10$.

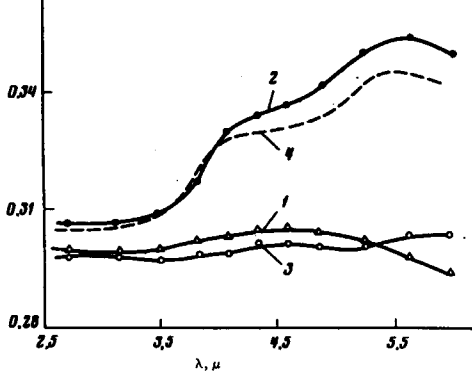


FIG. 2. Infrared reflection spectra in samples kept at $T = 300^\circ\text{K}$ for one hour prior to measurement, as a function of the temperature and the annealing time: 1— 90°K , 2— 280°K , two hours annealing; 3— 290°K , one hour annealing; 4—theoretical curve calculated for both types of drops, with concentrations $n_0 = 2 \times 10^{20} \text{ cm}^{-3}$ and $n'_0 = 1 \times 10^{20} \text{ cm}^{-3}$, $\omega_p \tau = \omega'_p \tau' = 30$, relative fraction of the light reflected from each group of drops 3%, concentration of interdrop medium $1 \times 10^{19} \text{ cm}^{-3}$.

V-sec^[3] in $n\text{-Si}$ at $N_0 \approx 2 \times 10^{20} \text{ cm}^{-3}$), as well as the influence of the acoustic scattering, point to a strong correlation in the arrangement of the ions (assumed in the initial model of^[11]), which causes a weakening of the electron-impurity scattering.

Maintaining the sample at room temperature usually led to a rapid (within one hour) vanishing of the minima on the $R(\lambda)$ curve, and the additional minimum at $\lambda = 3.8 \mu$ vanished much more rapidly than the principal minimum. This is apparently due to the capture of the Li ions by the surface faults and by the vanishing of the free electrons. Subsequent grinding and polishing of the sample restored the initial form of the $R(\lambda)$ curve.

In many cases, in samples kept for an hour at room temperature in a vacuum cryostat and again cooled to $T = 90^\circ\text{K}$, the $R(\lambda)$ spectrum differed strongly from the initial one. Figure 2 shows an example of the new $R(\lambda)$ dependence for a sample whose initial spectrum corresponded to curve 1 of Fig. 1. Instead of a minimum at $\lambda = 3.8 \mu$ and a subsequent decrease of R with increasing

of two distinct humps. When the temperature is slowly raised (in the course of several hours) from 250°K , the amplitudes of the humps increase, and then decrease again until they vanish completely and irreversibly. Such unusual plots of $R(\lambda)$ can be explained by assuming that maintaining the samples at room temperature led to a depletion of the near-surface region of the sample, due to the binding of the Li with surface centers. The light then begins to penetrate into the interior of the sample and is reflected from drops that are far from the surface (and have as a rule a long lifetime determined by the removal of the Li in the form of a precipitate into the volume of the sample). Analysis shows that in this case there should be observed not a minimum but a rise of $R(\lambda)$. It turned out that the plasma reflection minimum can rise only under the condition that the dielectric constant $\epsilon_0(\omega)$ of the reflecting object is larger than the dielectric constant $\epsilon_m(\omega)$ of the surrounding medium (at $\omega < \omega_p$). In our case, to the contrary, we always have $\epsilon_0(\omega) < \epsilon_m(\omega)$, and only an increase of $R(\lambda)$ should be observed. The observed additional rise at $\lambda = 5 \mu$ corresponds to $N_{Li} = n'_0 = 1 \times 10^{20} \text{ cm}^{-3}$. The constructed calculated dependence for this case (curve 4 of Fig. 2) agrees well with the experimental curve.

Thus, an analysis of the reflection spectra of strongly doped Si(Li) confirms our assumptions that a spatially inhomogeneous distribution of Li with rigorously fixed values of the concentration is produced in the strongly doped regions: 2×10^{20} and $1 \times 10^{20} \text{ cm}^{-3}$. The small observed amplitude of the signal from these regions (1–3%) is due, in our opinion to the finely-dispersed state of the drops, which determines the small fraction of the reflected light. In addition, as already indicated, the drops are effectively absorbed and are destroyed by the surface of the sample.

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