

Plasma reflection of valence electrons in germanium and silicon

O. A. Makarov, I. G. Neizvestnyi, and M. P. Sinyukov

Institute of Semiconductors, Siberian Branch of the Academy of Sciences of the USSR, Novosibirsk

(Submitted 29 March 1983)

Pis'ma Zh. Eksp. Teor. Fiz. 37, No. 10, 476-479 (20 May 1983)

The ultraviolet transparency of germanium and silicon beyond the plasma edge of the reflection of valence electrons is observed for the first time on a setup using the synchrotron radiation channel in the VÉPP-2M storage ring.

PACS numbers: 78.40.Kc, 78.20.Dj

The reflectivity of semiconductors rapidly decreases in the ultraviolet (UV) region of the spectrum and near 20 eV it is $\sim 1\%$. This behavior is attributable to the drop in the intensity of electronic transitions from the valence band to the conduction band. If the optical constants of the semiconductor are determined and the sum of oscillator strengths for these transitions is calculated, then in most cases it is already exhausted at quantum energies ~ 10 eV.¹ At high energies, the optical constants of the semiconductor are determined by the collective properties of valence electrons, which behave as free electrons at these frequencies.

In contrast to the infrared (IR) region of the spectrum, where the plasma reflection characteristics of the semiconductor are due to the free electrons in the conduction band, in the UV region, it is impossible to observe the characteristic minimum in the plasma reflection spectrum of valence electrons. This is due to the fact that plasma oscillations of electrons in the conduction band occur in a medium with a static polarizability of valence electrons ($|\epsilon_0^v| \gtrsim 10$), while the oscillations of electrons in the valence band occur in a medium with the static electronic polarizability if the deeper levels of the ionic core ($|\epsilon_0^d| \approx 1$).

When the frequency of the incident light exceeds the plasma frequency ($\omega > \omega_p$), the reflectivity of the semiconductor passes through a minimum and reaches a value determined by the static polarizability of the medium (ϵ_0):

$$R = \left| \frac{\sqrt{\epsilon_0} - 1}{\sqrt{\epsilon_0} + 1} \right|^2$$

It is evident that the more ϵ_0 differs from unity, the higher is the reflectivity of the semiconductor at frequencies $\omega > \omega_{\min}$. Since the polarizability of deep levels is small, the reflectivity of the semiconductor in the UV region of the spectrum at frequencies $\omega > \omega_p$, after reaching the minimum, does not increase as in the IR region of the spectrum, but remains at the level of this minimum. In this connection, for finite values of the relaxation time τ , leading to broadening of the spectral characteristics, the presence of the plasma edge cannot be determined by recording the reflection spectrum of the semiconductor. To determine the position of the plasma edge, it is

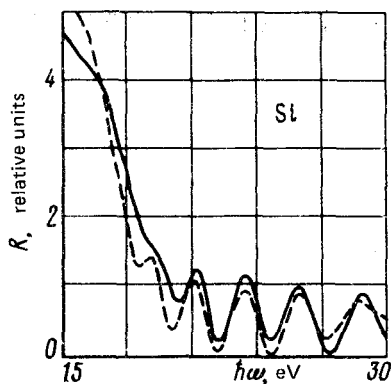


FIG. 1. Measured reflection spectrum of a silicon film on sapphire. s —Polarization, $\alpha = 15^\circ$, $d = 1750 \text{ \AA}$ (solid line). The dashed line shows the computed spectrum.

possible to use the fact that the semiconductor must be transparent at frequencies $\omega > \omega_p$. Selecting the thickness of the semiconductor film comparable to the wavelength of light, it is possible to observe an interference pattern for $\hbar\omega > \hbar\omega_p$, which will permit determining the position of the plasma edge exactly.

To record the reflection spectra, single-crystalline films of Ge and Si were grown on gallium arsenide and sapphire substrates. The spectra were recorded on a setup using the synchrotron radiation channel of the VEPP-2M storage ring.²

The measured spectra are represented by the solid lines in Figs. 1 and 2. From these spectra we can conclude that the position of the plasma edge for both semiconductors is close to 16 eV. To obtain more accurate values of the plasma frequency $\hbar\omega_p^v$, we use the equation for reflection by a multilayer system into which the dependence $\epsilon(\omega)$, which describes the plasma properties of valence electrons, was substituted; the plasma frequency and relaxation time were adjustable parameters. The plasma fre-

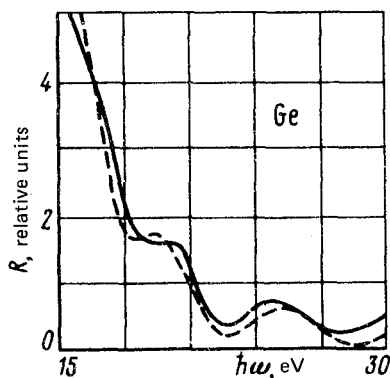


FIG. 2. Measured reflection spectrum of a germanium film on gallium arsenide. s —Polarization, $\alpha = 10^\circ$, $d = 750 \text{ \AA}$ (solid line). The dashed line represents the computed spectrum.

quencies, which were calculated for the valence electron gas in Ge ($N_v = 1.78 \times 10^{23} \text{ cm}^{-3}$) and Si ($N_v = 2.0 \times 10^{23} \text{ cm}^{-3}$), are 15.6 and 16.6 eV.

The dependence $\epsilon(\omega)$ differs for germanium and silicon due to the proximity of the 3d level in germanium to the valence band. For the range of frequencies in which the sum of oscillator strengths for transitions from the valence band to the conduction band is exhausted, the expression for $\epsilon(\omega)$ for Si, according to Ref. 1, has the form

$$\epsilon(\omega) = 1 - m_0^{-1} (e/\pi)^2 \int d^3k \sum_{l > v} f_{vk} f_{lv} g_{lv}.$$

This expression describes the contribution of electrons in the valence band to the dielectric constant. The integration here is performed over the Brillouin zone, while the summation is performed over all bands $l > v$, where V is the valence band. In connection with the absence of close-lying levels of the ionic core, the valence electrons in silicon undergo plasma oscillations in the medium with the vacuum dielectric constant and the frequency $\omega_p^v = 4\pi N_v e^2 / m_0$ is determined only by the concentration of valence electrons. For germanium, at frequencies for which the sum of oscillator strengths of the valence band is exhausted, but transitions from the d level are still energetically impossible, we have

$$\epsilon(\omega) = 1 - m_0^{-1} (e/\pi)^2 \int d^3k \sum_{l > v} f_{vk} f_{lv} g_{lv} - m_0^{-1} (e/\pi)^2 \int d^3k \sum_{l > v} f_{dk} f_{ld} g_{ld}^R.$$

This expression differs from the analogous expression for silicon by a term which includes the contribution of d electrons to polarizability. In these expressions f_{vk}, f_{dk} is the single-frequency Fermi distribution, f_{lv}, f_{ld} is the oscillator strength for corresponding bands, g_{lv}, g_{ld} are terms that include the finiteness of the relaxation time. The plasma frequency of valence electrons in Ge differs from the frequency of free electrons due to the term which includes the interaction of valence electrons with electrons in the d level and the static polarizability of d electrons.

The calculation was performed on a computer by solving the system of linear equations obtained by expanding the theoretical dependence with respect to the adjustable parameters up to terms containing the first derivatives. Minimum mean-square error was used as the criterion for a valid fit. The dashed lines in Figs. 1 and 2 show the results of a calculation with the following parameters: $\hbar\omega_p^v = 16.34 \pm 0.02$ eV and $\hbar/\tau = 0.46 \pm 0.01$ eV for Si (Fig. 1) and $\hbar\omega_p^v = 15.81 \pm 0.08$ eV and $\hbar/\tau = 2.17 \pm 0.06$ eV for Ge (Fig. 2). These values of the plasma frequency $\hbar\omega_p^v$ agree well with the values obtained in Ref. 1 based on measurements of the optical constants of germanium and silicon.

In conclusion, we thank E. S. Gluskin and the staff of the VÉPP-2 facility at the Institute of Nuclear Physics of the Siberian Branch of the Academy of Sciences for help in performing the experiments.

¹H. R. Phillip and H. Ehrenreich, *Semiconductors and Semimetals*, Ed. by Willardson and Beer 1976, Vol. 3.

²E. S. Gluskin, V. M. Zakharov, O. A. Makarov, and M. P. Sinyukov, *Proceed. Intern. X-Ray and VUV-Synchr. Rad. Instrum. Conf.*, Hamburg, 1982.