# Multioscillation electroreflection spectra of germanium

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It is shown that when nonequilibrium depletion is produced in the space-charge region of a semiconductor it is possible to increase the degree of homogeneity of the electric field when the electroreflection spectra are recorded and to observe a sufficiently large number of oscillations to reveal effects of non-parabolicity of the bands.

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The spatial inhomogeneity of the field in a semiconductor at the depth of penetration of the light can lead to a complete damping of the Franz-Keldysh oscillations in the experimental electroreflection spectra.[1,2] To exclude this inhomogeneity it is necessary to satisfy the criterion[3]

$$\frac{R_1}{|2k|} \ll 1,$$

where

$$R_1 = \left|\frac{1}{\mathcal{E}}\frac{d\mathcal{E}}{dz}\right|_{z_s}$$

is the relative electric field gradient, $1/|2k| = \lambda/4\pi\sqrt{n^2+k^2}$ is the effective depth of penetration of the light, and $z$ is the coordinate in the interior of the semiconductor ($z_s$ is its value on the surface); this criterion calls for conditions that minimize $R_1$. This quantity decreases with increasing depth of penetration of the field into the semiconductor, i.e., when the spectrum is recorded it is necessary to modulate the surface field in such a way that depletion takes place in the space-charge region (SCR). To obtain homogeneous electroreflection (ER) spectra at large field intensity and with depletion in the SCR, Handler and co-workers[4] used samples doped with impurities. They succeeded in observing for the first time three additional oscillations in the ER spectrum on the fundamental absorption edge of germanium by an electrolytic method. Comparison with the theory has shown that the experimental spectrum can be adequately described by using constant interband reduced masses. It is known that when the photon energy deficit $|E_g - \hbar\omega|$ is increased to a value on the order of the spin-orbit splitting, effects of nonparabolicity of the band should come into play. However, Handler *et al.*[4] did not succeed in obtaining a sufficiently large number of oscillations to be able to observe these effects. In later studies,[5] in which the Schottky barrier was used, the conditions were likewise not optimal to obtain high homogeneity of the field. It is therefore of interest to study the ER spectra with large numbers of oscillations filling the energy gap from $E_0$ to $E_0+\Delta_0$; this is the subject of the present communication.

The dependence of the inhomogeneity parameter $R_1$ on the electric field was

  

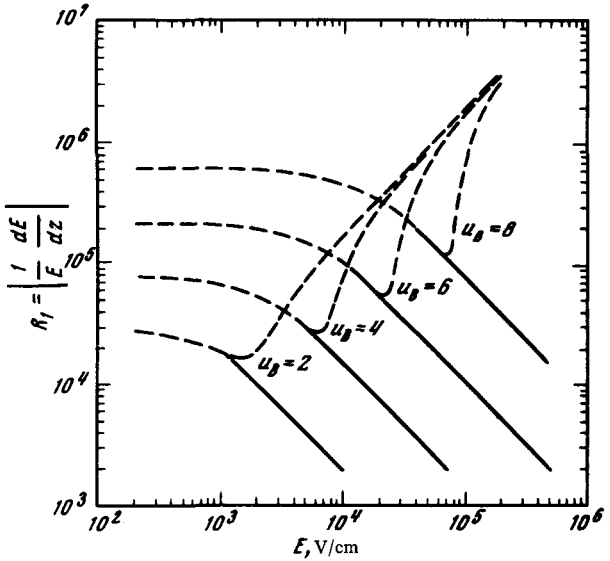


FIG. 1. Dependence of the inhomogeneity parameter $R_1$ on the surface field for different sample doping levels as determined by the volume potential $U_B$. Solid lines—nonequilibrium case in SCR, dashed—equilibrium case.

calculated in[3] for different sample-doping levels under conditions of equilibrium in the SCR. This dependence is shown by the dashed lines of Fig. 1. It is seen that $R_1$ reaches a minimum at a definite value of the field intensity for each doping level. Subsequent increase of $R_1$ with increasing field is due to the formation of an inversion layer in the SCR. This can be avoided by producing a nonequilibrium depletion near the surface. The case of nonequilibrium depletion can be realized in metal—insulator—semiconductor (MIS) structures at high modulation frequencies ($\gtrsim 10^4$ Hz) or else in metal—semiconductor structures (Schottky barrier), when no minority carriers are accumulated in the SCR. In some cases this situation will be realized in electrolyte—semiconductor systems. The use of Schottky barriers to record "homogeneous" ER spectra seems preferable, because the potential fluctuations, which are determined by the fluctuations of the surface charge in the MIS structures, will manifest themselves in a Schottky barrier to a much lesser degree, because of the screening action of the metallic surface.

In the case of a Schottky barrier, the field attenuates in the interior of the semiconductor in accordance with the law

$$\mathcal{E}(z) = \mathcal{E}(z_s)\left(1 + \frac{z}{W}\right),$$

where $W = \epsilon_0 \epsilon \mathcal{E}(z_s)/qn_0$ is the thickness of the depletion layer, $\epsilon_0$ and $\epsilon$ are the dielectric constants of the vacuum and of the semiconductor, respectively, $n_0$ is the equilibrium concentration of the electrons, and $q$ is the electron charge. We then obtain for the parameter $R_1$ the expression

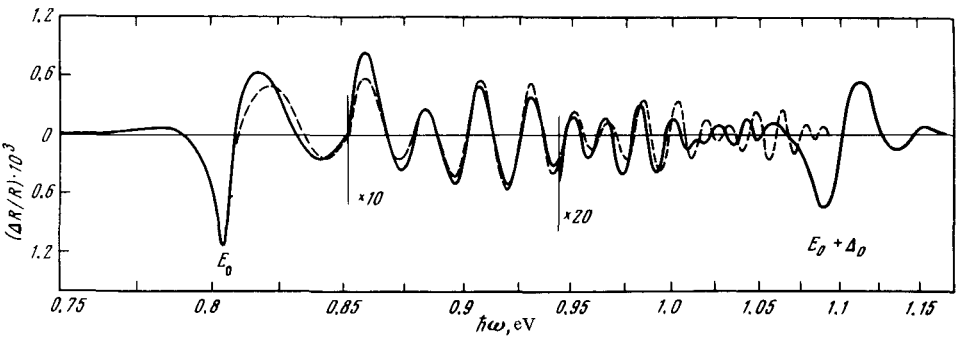


FIG. 2. Solid line—ER spectrum obtained on a Schottky barrier for the transitions $E_0$ and $E_0+\Delta_0$ of Ge. $T=300$ °K, $\mathcal{E}=2.28\times10^4$ V/cm, $\mathcal{E}\parallel[111]$, optical-wave polarization vector $\mathbf{e}\parallel[110]$. Dashed line—theoretical ER spectrum obtained by using constant reduced masses. The amplitude of this spectrum, starting with 0.85 eV, is magnified five times. The change of the amplitude of the experimental spectrum is shown in the figure.

$$R_1=\frac{qn_0}{\mathcal{E}(z_s)\epsilon_0\epsilon},$$

The dependence of $R_1$ on the field and on the concentration is shown for this case by the solid lines of Fig. 1. It is seen from the figure that with increasing electric field, in the case of the Schottky barrier, a more homogeneous perturbation will be realized in the more intrinsic semiconductor. An estimate based on the solution of the diffusion equation for the flux minority carriers in the SCR has shown that minimum donor densities sufficient to produce a Schottky barrier in germanium at room temperature is $\sim10^{14}$ cm$^{-3}$.

Figure 2 shows the ER spectrum obtained on the (111) surface of $n$-Ge with concentration $N_d=1.3\times10^{14}$ cm$^{-3}$. The spectrum reveals three irregularities of the amplitude of the oscillating part. These beats are due to the superposition of oscillations caused by the light and heavy hole bands.[4]

The dashed line is the algebraic sum of the two electro-optical functions $G(\eta_l)$ and $G(\eta_h)$ for the light and heavy hole bands, respectively, and

$$\frac{\Delta R}{R}=\frac{A}{\hbar\omega^2}[BG(\eta_l)+G(\eta_h)],$$

where $A$ is an amplitude factor, $B$ is the ratio of the contributions of the light and heavy holes, $\eta$ is a dimensionless parameter that includes the reduced masses in the field direction. These masses were chosen in accordance with[6] and their values are $\mu_l=0.0196\,m_e$, $\mu_h=0.0354\,m_e$, $m_e=0.038\,m_0$, where $m_0$ is the mass of the free electron. This theoretical spectrum is probably not an exact fit near the center of the Brillouin zone (in the region of the maximum of

$E_0$), owing to degeneracy effects and the Coulomb interaction. In the region of the second to the sixth oscillations, the theory was in agreement with experiment, but a discrepancy appears starting with the second beat. This means that the experimental spectrum cannot be completely described by using constant reduced masses.

In the region of the second and third beats, the transitions from the band of the heavy holes are localized in k space farther from the center of the Brillouin zone than the transitions from the band of the light holes. Therefore the discrepancy between experiment and theory is due more readily to the change in the reduced mass for the heavy-hole band. It was found that in order for the theory to agree with experiment the new "nonparabolic" reduced mass must satisfy the relation

$$\mu_h^* = \mu_h + 0.0735 m_0 (\hbar\omega - E_g)^2,$$

where $\mu_h = 0.0354\ m_0$ is the reduced mass obtained in the approximation in which the bands are parabolic.


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