

Influence of cooling of an electron gas in ion-bombarded layers on the photoluminescence of GaAs

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1. There have been many investigations (see, for example, Refs. 1-6) of the hot-electron photoluminescence in the case of surface absorption of the exciting light in crystals with a short diffusion length L_D . However, the effects of surface cooling¹⁰ have been ignored in considering the heating of carriers near the surface.⁷⁻¹⁰ This cooling can influence the photoluminescence spectra if L_D is of the order of, or less than, the cooling length l_c , which is true at $\leq 80^\circ\text{K}$ in the case of GaAs (Refs. 11 and 12). It should be pointed out that cooling on the surface is important also for $L_D \gg l_c$ when the thickness of a sample $2d$ satisfies $2d \leq l_c$.

2. Investigations of the photoluminescence excited by a cw He-Ne laser (excitation rate $\sim 10^{18}$ photons $\cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$) were carried out on $10\text{-}\mu$ thick n-type GaAs films grown by liquid epitaxy on semiinsulating gallium arsenide substrates. The majority-carrier density in the films was $10^{14}\text{-}10^{16} \text{ cm}^{-3}$ and their mobility was $\sim 6000 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{sec}^{-1}$ at 300°K .

Carriers were heated by an electric field of 1000-1200 V/cm intensity (which was the maximum possible field in the prebreakdown range). There was no change in the form of the photoluminescence spectrum (within the limits of the experimental error) in weaker fields. Heating of the crystal lattice was avoided by the application of the electric field in the form of pulses of $\sim 0.9 \mu\text{sec}$ duration and 100 Hz repetition frequency. The voltage was applied via a pulse amplifier connected to a G5-13 generator. The photoluminescence was analyzed with an MDR-2 monochromator, FÉU-62 photomultiplier, and S7-8 oscilloscope.

The state of the surface was altered by low-energy ($E = 1 \text{ keV}$) bombardment with argon ions, which perturbed a layer $\leq 50 \text{ \AA}$ thick and resulted, firstly, in an increase in the concentration of nonradiative centers and in surface

damage (and, consequently, in a reduction in the mobility in the damaged layer and in an increase of S_E , which was the cooling rate on the surface introduced in Ref. 10) and, secondly, in the appearance of surface luminescence centers.^{13,14} One should point out particularly that when a damaged layer $\sim 50 \text{ \AA}$ thick was etched away, the photoluminescence spectrum (recorded in the absence or presence of a field) was identical with the spectrum obtained for the original samples before irradiation.

3. We shall first consider the photoluminescence spectra determined at 80°K . In the absence of an electric field there was a band with a maximum at 1.507 eV (Fig. 1a). The quadratic dependence of the intensity on the rate of excitation originated from the interband recombination. By analogy with Refs. 2-6, the application of a field broadened the band recorded for the original surface and the broadening was in the direction of shorter wavelengths. After argon-ion bombardment with a dose of $D = 10^{14} \text{ cm}^{-2}$ the broadening became much smaller and for high doses D the broadening was too small to be measured.

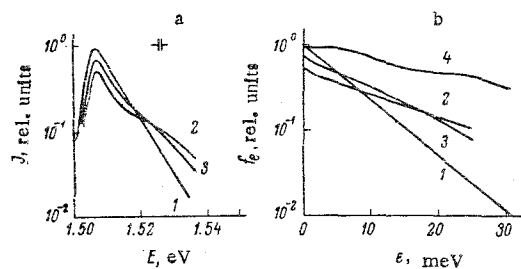


FIG. 1. Photoluminescence spectra (a) and electron distribution functions (b) of n-type GaAs at 80°K in the absence (1) and presence (2, 3) of an electric field of 1.2 kV/cm intensity: 1, 2) original surface; 3) surface irradiated with Ar ions (dose $D = 10^{14} \text{ cm}^{-2}$); 4) electron distribution function calculated in Ref. 6 for $F = 0.9 \text{ kV/cm}$.

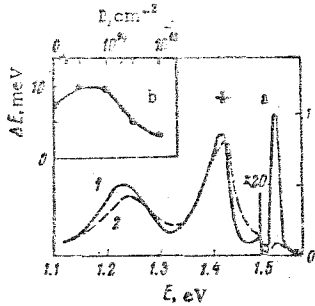


FIG. 2. a) Photoluminescence spectra of irradiated (with a dose of $D = 10^{14} \text{ cm}^{-2}$) n-type GaAs at 4.2°K in the absence (1) and presence (2) of an electric field of 1 kV/cm intensity. b) Shift of the maximum of the 1.23 eV band in a field, plotted as a function of the radiation dose.

A study of the influence of an electric field F on the interband luminescence spectrum at 77°K was investigated in Refs. 5 and 6 and a determination was made of the energy distribution function of the field-heated electrons, which was compared with the function calculated by the Monte Carlo method (on condition that this function was independent of the coordinate). Assuming this condition and also bearing in mind that the effective mass of holes is large compared with the effective mass of electrons (so that only the electrons are heated), we find that

$$\frac{J_F(E - E_g)}{J_0(E - E_g)} \approx \frac{f_F(\epsilon)}{f_0(\epsilon)} \quad (1)$$

where $f_F(\epsilon)$ and $f_0(\epsilon)$ are the normalized to unity $[\int_0^\infty f_{F,0}(\epsilon) d\epsilon = 1]$ electron distribution functions in the presence and absence of the field, respectively; E is the energy of the luminescence photons; E_g is the band gap; $\epsilon = E - E_g$; $g(\epsilon)$ is the density of states.

Figure 1b gives $f_F(\epsilon)$ and it demonstrates that the experimental function $f_F(\epsilon)$ deduced from Eq. (1) and from the curves in Fig. 1a differs greatly from the theoretical function obtained in Ref. 6, and this difference increases after irradiation. The actual nature of the dependence of f_F on ϵ is not specified in deducing these curves but we can see from Fig. 1b that in a wide range of energies the curves can be approximated by the Maxwellian function with an effective electron temperature¹⁾ T_e .

$$f_F(\epsilon) = CT_e^{-3/2} \exp\left(-\frac{\epsilon}{kT_e}\right), \quad (2)$$

which is 180, 130, and 320°K respectively for curves 2, 3, and 4 in Fig. 1b. An analogous reduction in T_e due to carrier cooling on the surface has been observed earlier⁸ in a study of the conductivity of n-type Si. In Ref. 6, where cooling on the surface is ignored, the theoretical and experimental functions $f_F(\epsilon)$ are matched on the assumption that the mean free path of carriers is extremely short so that, in the Monte Carlo calculations, the concentration of ionized impurities is assumed to be three orders of magnitude higher (!) than the actual concentration in the sample.

4. We investigated the influence of the application of an electric field at 4.2°K on the photoluminescence bands due to radiative recombination via centers with energy levels located in the band gap. It was established earlier (Ref. 15) that the 1.515 and 1.23 eV lines were due to quasibulk luminescence centers located at a depth equal to the diffusion length. The photoluminescence bands in

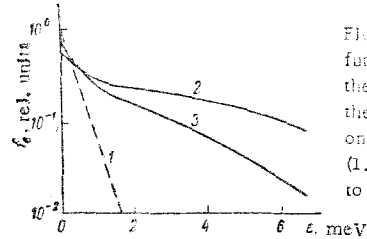


FIG. 3. Electron energy distribution functions of n-type GaAs at 4.2°K in the absence (1) and presence (2, 3) of the electric field. Curve 2 is plotted on the basis of the data in Fig. 1a (1.23 eV band); curve 3 corresponds to the 1.42 eV band.

Fig. 2a were identified as follows. The 1.515 eV line was attributed to the residual Si occupying Ga vacancies and the 1.23 eV band was attributed to gallium vacancies forming luminescence centers.²⁾ The 1.42 eV band was assigned to radiative surface structure defects of the acceptor type.¹⁶ The intensity of the 1.515 eV line fell steeply on application of the field, which had been reported earlier¹⁻⁴ and attributed to the impact ionization of the appropriate shallow centers. Strong quenching of this line prevented a study of changes in its profile due to the application of a field. However, such changes were observed for the other two bands and the shift of the maximum of the 1.23 eV band in the field became weaker on increase of the radiation dose (Fig. 2b). The shift of the 1.42 eV band after the optimal dose (10^{14} cm^{-2}) was considerably less than the shift of the 1.23 eV band and, when the dose D was increased, there was no shift of the 1.42 eV band in the applied fields.

Application of a familiar relationship¹⁷ for the short-wavelength edge of a photoluminescence band governed by acceptor centers made it possible to determine the electron distribution functions (Fig. 3) at 4.2°K in the same way as in Refs. 5 and 6. A considerable difference was found between the distribution functions obtained for the same dose D from the surface (1.42 eV) and bulk (1.23 eV) bands. Approximation of the logarithms of the distribution functions with straight lines (beginning from $\epsilon = 2 \text{ meV}$) made it possible to estimate the electron temperature in a 50 Å surface layer, which was $\approx 20^\circ\text{K}$, as well as the electron temperature averaged (by analogy with Fig. 1b) over the diffusion length, which was $\approx 40^\circ\text{K}$.

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¹⁾It follows from Ref. 10 that in general, the electron temperature T_e is a function of the distance from the surface and, therefore, the values of T_e obtained by us are, in fact, averaged over the diffusion length.

²⁾This band was in some cases due to the recombination via donor-acceptor pairs and in others due to recombination via acceptor centers. Our experiments (particularly those on the luminescence kinetics) showed that the latter was true in our case.

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