Low-energy cathodoluminescence experiment with polarized electrons and a negative-electron-affinity GaAs target

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We report new measurements of circularly polarized recombination radiation from highly doped p-type GaAs emitted under impact of longitudinally polarized electrons with an initial kinetic energy varied between 2 and 10 eV. The work function of the target crystal is lowered by cesiation and oxidation of the surface. The results are discussed and compared with our earlier measurements on a clean GaAs crystal surface and with photoluminescence data.

INTRODUCTION

Our first measurements of the circular polarization of the recombination radiation from clean GaAs emitted under impact of polarized electrons were communicated in a previous paper.[1] Therein we discussed in detail that this circular polarization P_{circ} is directly related to the electron polarization P_r at the instant of recombination. For our experimental conditions, the relation is

$$P_{\mathrm{circ}} = \pm\tfrac{1}{2}|P_r| \ . \tag{1}$$

Spin-relaxation processes reduce the initial polarization P_i of the incoming electrons to the polarization P_r. The measurement of P_i and the determination of P_r by measuring P_{circ} [according to Eq. (1)] allow conclusions about the depolarization of electrons in the conduction band.

The efficiency of the depolarization processes and the probability of electron-hole pair creation by the injected electrons (this process leads to a further reduction of the conduction-band electron polarization) decrease with decreasing electron energy. In order to achieve a low initial electron energy E_0 in the conduction band, it is necessary to lower the work function of the target crystal.

Figure 1 shows the energy relations between source and target and illustrates the differences between a clean target-crystal surface and a cesiated and oxidized one. In the source, photons of an energy $h\nu$ excite electrons from the valence band (VB) to the conduction band (CB). The work function ϕ_S is lowered below the minimal band gap E_{gS}, therefore the electrons can leave the crystal. V_a indicates the applied potential difference between the Fermi levels E_{FS} and E_{FT} of source and target, respectively. Without lowering of the work function ϕ_T, it is not possible to attain a kinetic energy E_0 of the electrons that is smaller than E_{min} ($E_{\mathrm{min}} = \phi_T - E_{gT} \approx 3.5$ eV; $\phi_T \approx 5$ eV for clean GaAs,[2] the minimal band gap $E_{gT} = 1.504$ eV for GaAs at 90 K crystal temperature[3]). With cesiation and oxidation of the target surface the increase in kinetic energy for the electrons entering the target can be avoided. Then it is possible to attain an energy $E_{0,\mathrm{min}} < 3.5$ eV by applying a suitable small voltage V_a.

With optical excitation in the target it is not possible to create highly polarized conduction-band electrons of more than a few tenths of an eV initial energy, because the initial polarization decreases rapidly with increasing excitation energy.[4] In our low-energy cathodoluminescence experiment, the initial polarization of the conduction-band electrons is independent of their initial kinetic energy. Therefore we obtain information about the depolarization of the conduction-band electrons in an

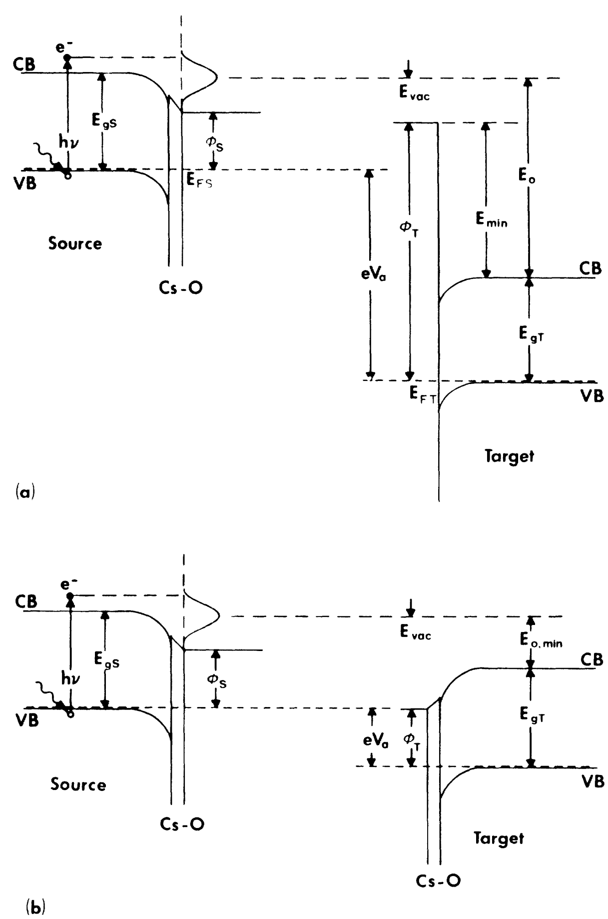

FIG. 1. Energy relations between source and target. (a) Clean target surface; (b) cesiated and oxidized target surface. (Further explanations are in the text.)

energy range that is not accessible in polarized photoluminescence.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement has been described in detail elsewhere.[1,5] The polarized-electron source contains a $GaAs_{0.6}P_{0.4}$ photocathode, illuminated by circularly polarized light from a krypton-ion laser ($h\nu=1.916$ eV). An electrostatic 90° deflector takes the electron beam out of the light path. In a solenoid the electron spins are rotated by 90° around the beam direction. After a second 90° beam bend, the electrons are again longitudinally polarized. They impinge perpendicularly onto a (100) surface of a highly doped p-type GaAs crystal ($N_A=1.6\times10^{19}$ atoms/cm^3). The GaAs target can be cesiated and oxidized to obtain a negative-electron-affinity (NEA) surface similar to the procedure used in the source preparation.[6]

Instead of producing the circularly polarized recombination radiation by electron impact, we can also illuminate the target crystal with circularly polarized light of a He-Ne laser ($h\nu=1.959$ eV). This allows us to do low-energy cathodoluminescence and polarized photoluminescence measurements with the same target crystal.

The light, emitted from the target, is reflected by a plane mirror into the light-polarization analyzer, which is located outside the vacuum chamber. The polarization of the electron beam is measured by means of an absorbed-current polarimeter employing a tungsten crystal.[7]

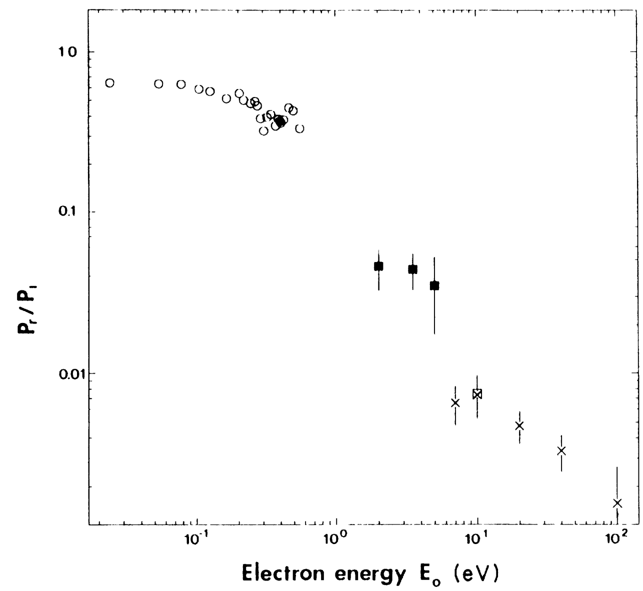

FIG. 2. The ratio of the polarization P_r of the conduction-band electrons at the instant of recombination to the initial electron polarization P_i, plotted vs the initial electron energy E_0. Results of cathodoluminescence and photoluminescence measurements obtained with GaAs target crystals are shown. Cathodoluminescence: NEA GaAs target (■); clean GaAs target (□, ×). Photoluminescence: data from Zakharchenya *et al.* (Ref. 9) (○); this work (●). (Further explanations are in the text.)

MEASUREMENTS

The circular polarization of the emitted recombination radiation from the liquid-nitrogen-cooled GaAs target ($T=90$ K) was measured as described in our previous publication.[1] Before each measurement the target-crystal surface was cesiated and oxidized. The existence of a NEA surface was controlled by observing the photocurrent from the target under illumination with the He-Ne laser. The initial electron energy was varied between 10 and 2 eV. For an electron energy lower than 2 eV the intensity of the emitted light was too weak for polarization analysis.

To compare our cathodoluminescence data with photoluminescence data we also measured the circular polarization of the emitted light from the clean GaAs surface by excitation with circularly polarized light.

RESULTS AND DISCUSSION

Figure 2 shows the ratio of the polarization P_r of the conduction-band electrons at the instant of recombination to the initial electron polarization P_i versus the initial electron energy E_0. P_r was determined from the circular polarization of the emitted light according to Eq. (1). The solid squares represent our new results obtained with the NEA GaAs surface and the open square at $E_0=10$ eV is obtained with the same crystal, but with a clean GaAs surface. The crosses indicate the data we achieved with a different clean GaAs crystal of nearly identical acceptor concentration ($N_A=2\times10^{19}$ atoms/cm^3).[1] The polarization values at $E_0=10$ eV are in good agreement, which should be expected for identical electron energy and crystals of similar acceptor concentration and temperature. The polarization increases further with decreasing electron energy. This is mainly seen as a consequence of the decreasing number of electrons excited from the valence band into the conduction band by the electron-hole pair creation process. Moreover, the depolarization of the injected electrons by the D'Yakanov-Perel' process is less effective for lower initial electron energy.[1,8]

For comparison, photoluminescence data are also shown in Fig. 2. The open circles indicate the measurements of Zakharchenya *et al.*[9] and the solid circle represents our result. In photoluminescence experiments, the circular polarization of the emitted light is measured as a function of the incident photon energy $h\nu$. By assuming parabolic bands, the initial kinetic energy E_0 of electrons excited from the valence band to the conduction band by photons of energy $h\nu$ can be calculated by

$$E_0=(h\nu-E_{gT})\frac{m_h}{m_h+m_e} , \qquad (2)$$

where m_e and m_h are, respectively, the effective masses of the conduction-band electrons and the valence-band holes. Here, photoluminescence data are plotted versus the initial kinetic energy of the electrons excited from the upper valence band (the heavy-hole band with $m_h=0.48m_0$ and $m_e=0.067m_0$, where m_0 is the freeelectron mass).[10] For $h\nu > E_{gT}$ there are always some electrons originating from the light-hole band, and for $h\nu \gtrsim E_{gT} + \Delta$ some electrons originating from the split-off band, where Δ is the split-off energy of GaAs at 90 K of $\Delta = 0.34$ eV.[11] These electrons, which have a lower kinetic energy than the ones coming from the heavy-hole band are disregarded by us. The initial conduction-band electron polarization P_i in the photoluminescence measurements was calculated after D'Yakanov and Perel'.[4] P_r was determined using Eq. (1).

CONCLUSION

We extended our polarized cathodoluminescence measurements down to 2 eV initial electron energy. By combining these data with the polarized photoluminescence data of Zakharchenya *et al.*[9] between 0.02 and 0.6 eV, we get information about the circular polarization of the light emitted in the recombination of polarized electrons in GaAs over the large energy range from 0.02 to 100 eV.

As a consequence of space-charge-related intensity problems, we could not measure below an initial electron energy of 2 eV. Therefore, electron-hole pair creation could be reduced but not avoided up to now and the excitation of electrons into the conduction band might have led to a reduced polarization even at our lowest energy of 2 eV.[1]

In cathodoluminescence experiments below $E_{gT} = 1.504$ eV, the polarization of the conduction-band electrons is definitely not reduced by electron-hole pair creation. Therefore, such data—although difficult to obtain for us because of the very low light signal—would provide very interesting information about the mechanisms of electron depolarization inside the crystal.

Another way of closing the still remaining energy gap between 0.6 and 2 eV could be a careful measurement of the very small circular polarization of the recombination radiation expected in polarized photoluminescence experiments at higher excitation energy.[4,9]

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