Emission of circularly polarized recombination radiation from p-doped GaAs and GaAs$_{0.62}$P$_{0.38}$ under the impact of polarized electrons

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Circularly polarized light is emitted in radiative transitions of polarized electrons from the conduction to the valence band in GaAs or GaAs$_{1-x}$P$_x$ crystals. The degree of light polarization is directly related to the polarization of the conduction-band electrons at the instant of recombination and allows conclusions about the depolarization of electrons in the conduction band. The depolarization is caused by spin-relaxation processes. The efficiency of these processes depends on crystal type, crystal temperature, degree of doping, and kinetic energy of the electrons. Highly p-doped GaAs and GaAs$_{0.62}$P$_{0.38}$ crystals ($N_A > 1 \times 10^{19}$ atoms/cm^3) were bombarded with polarized electrons (initial polarization 38%), and the spectral distribution and the circular polarization of the emitted recombination radiation were measured. The initial kinetic energy of the electrons in the conduction band was varied between 5 and 1000 eV. The measurements of the spectral distribution show that the electrons are thermalized before recombination occurs, independent of their initial energy. An important thermalization process in this energy range is the excitation of crystal electrons by electron-hole pair creation. The circular polarization of the recombination radiation lies below 1% in the whole energy range. It decreases with increasing electron energy but is still of measurable magnitude at 100 eV in the case of GaAs$_{0.62}$P$_{0.38}$. The circular polarization is smaller for GaAs than for GaAs$_{0.62}$P$_{0.38}$, which we attribute to more efficient spin relaxation in GaAs.

I. INTRODUCTION

Highly p-doped GaAs and GaAs$_{1-x}$P$_x$ cyrstals irradiated by circularly polarized light of an energy slightly higher than the minimal band gap are very efficient sources of polarized electrons.[1-4] The process utilized in these sources is the optical excitation of electrons from the $P_{3/2}$ valence band to the $S_{1/2}$ conduction band followed by emission into the vacuum, facilitated by a cesiated and oxidized surface of a negative electron affinity.

The great success of these sources almost automatically led to interest in the inverse process, namely the emission of circularly polarized light under the bombardment with polarized electrons. In this connection it had already been discussed whether the inverse process could be utilized in measuring the polarization of electron beams.[5] The emission of circularly polarized light is expected from the transition probabilities, if polarized conduction-band electrons recombine with free states of the $P_{3/2}$ valence band (Sec. II A). The degree of circular polarization of the recombination radiation is directly related to the polarization of the electrons at the instant of recombination [Eq. (1)] and can therefore be used to determine the amount of depolarization which the electrons suffer between entrance into and radiative recombination in the cyrstal. However, it is a question of the efficiency of spin-relaxation processes in the conduction band whether a measurable electron polarization remains before recombination occurs.

It should be noted that the high degree of polarization of the electrons emitted from GaAs/GaAs$_{1-x}$P$_x$ sources is no warranty for a high degree of light polarization in the inverse process. Besides the fact that the light polarization is only one half of the electron polarization because of the transition probabilities, the different dwell times of the polarized electrons in the conduction band come into play: In the source the time is determined by the diffusion to the surface, in the inverse process the time is given by the (average) lifetime for radiative recombination which is usually longer and, therefore, more spin relaxation can take place. Another reason is given by the difference in the initial kinetic energy of the conduction-band electrons in the source process and our kind of inverse process: In the sources, the electrons have approximately thermal kinetic energy. In our experiment the energy was varied between 5 and 1000 eV. The electrons thermalize into the conduction-band minimum before they recombine (Sec. IV). An efficient thermalization process in this energy range is the excitation of crystal electrons (electron-hole pair creation), resulting in a mixture of injected and excited electrons in the conduction band. The electrons suffer depolarization during and after thermalization. In addition, the excited crystal electrons dilute the average polarization of all conduction-band electrons.

For both polarized electron sources and the inverse experiments high p doping of the cyrstals employed is essential. Our crystals have an acceptor concentration exceeding 10^{19} atoms/cm^3 (Sec. III). The doping causes a down-bending of the bands at the surface[6] which, in conjunction with the Cs/O layer, leads to the negative electron affinity (NEA) (Refs. 7 and 8) necessary to let the conduction-band electrons escape into the vacuum. In the inverse experiment the p doping is required in order

to provide holes for the recombination of the injected electrons. In addition, the high p doping is responsible for the fact that we were able to measure a finite polarization effect at all, because the efficiency of the spin-relaxation processes is doping dependent: From results obtained in polarized photoluminescence experiments[9] an electron polarization of unmeasurable low value at the instant of recombination must be expected in measurements with lightly doped crystals, if the initial kinetic energy of the conduction-band electrons exceeds a few tenths of an eV.

The measurements of the circular polarization of the recombination radiation emitted under impact of polarized electrons reported here are the first of this kind. A similar experimental program is under way elsewhere.[10] But there are some measurements on related processes, to which our results can be compared: In *polarized photoluminescence* experiments,[9,11−13] electrons are excited into the conduction band by circularly polarized light and the circular polarization of the emitted recombination radiation is determined. If the energy of the exciting photons exceeds the splitoff energy Δ of the valence bands [$\Delta = 0.25$ eV for $GaAs_{0.62}P_{0.38}$ (Ref. 14), $\Delta = 0.34$ eV for GaAs (Ref. 15)], excitations from the spin-orbit split-off valence band (the $P_{1/2}$ band) become possible. Then the initial conduction-band electron polarization decreases rapidly with increasing photon energy.[16] Therefore, it is impossible to create highly polarized conduction-band electrons of high initial kinetic energy by optical excitation. In our measurements, the initial polarization of the conduction-band electrons is independent of their initial energy. Thus, our measurements are an extension of the polarized photoluminescence measurements to higher energy. In fact, our experiment is a *low-energy cathodoluminescence* experiment with *polarized* electrons, which have not yet been employed in cathodoluminescence.

In a superficial way our experiment (incident electrons, emitted photons) could also be classified as "inverse photoemission spectroscopy (IPES)."[17−22] This, however, would be misleading since IPES is a method of investigating the energies of unoccupied bands, not processes in the conduction band. Furthermore, the published measurements on "spin-polarized IPES (SPIPES)" do not involve the analysis of the emitted-light polarization but rather the determination of an intensity asymmetry resulting from the spin-dependent interaction of the incident polarized electrons with the polarized bound electrons of ferromagnets.[20−22] For those reasons we do not use the term SPIPES for our experiment.

Our first results have already been communicated in a short publication.[23]

II. BACKGROUND

A. Recombination at the Γ point

In III-V semiconductors, band structure and transition probabilities near the Γ point are responsible for the possibility to generate polarized electrons by illumination with circularly polarized light.[2] In a similar way, they are responsible for the emission of circularly polarized light, if polarized electrons recombine with holes in the $P_{3/2}$ valence band at the Γ point in the inverse process. The degree of circular polarization is related to the polarization of the conduction-band electrons at the instant of radiative recombination just like the degree of conduction-band electron polarization in the sources at the instant of excitation is related to the circular polarization of the exciting light.

The circular polarization of the recombination radiation is given by[16]

$$P_{\text{circ}} = -\tfrac{1}{2}|P_r|\cos\phi , \tag{1}$$

where P_r is the degree of polarization of the conduction-band electrons at the instant of recombination and ϕ is the angle between the electron-polarization vector and the direction of light observation, corrected for refraction at the target surface. In our experiment, the electrons hit the target surface perpendicularly with a longitudinal polarization, oriented parallel or antiparallel to the direction of the target normal. The angle of observation, ϕ, is small (Sec. III); therefore, $\cos\phi \approx \pm 1$, where the sign depends on the orientation of polarization. Equation (1) is reduced to

$$2P_{\text{circ}} = \pm|P_r| . \tag{2}$$

The initial polarization of the electrons in the crystal, P_i, is larger than P_r because of the various depolarization processes (Sec. II C) which affect the electrons between entering and recombining. According to Eq. (2), the degree of polarization P_r of the recombining electrons is directly determined by measuring P_{circ}, and therefore the total amount of depolarization can be determined, because P_i is known from independent measurements with an electron polarimeter (Sec. III).

B. Initial kinetic energy of the electrons and thermalization

As mentioned above, our measurements of the spectral distribution of the emitted light (Sec. IV) indicate that the electrons are fully thermalized into the Γ minimum before recombining and that we only have to consider the recombination of electrons with holes in the $P_{3/2}$ valence band. Therefore, the very simple Eq. (2) retains its validity, independent of the initial kinetic energy of the conduction-band electrons.

However, the thermalization processes and the efficiency of the spin-relaxation processes are energy dependent, leading to an energy dependent P_r and P_{circ} [Eq. (2)], respectively: If the initial kinetic energy is higher than the minimal band-gap value E_g of the crystal [$E_g = 1.504$ eV for GaAs (Ref. 24); $E_g = 1.982$ eV for $GaAs_{0.62}P_{0.38}$ (Ref. 25) at 90 K crystal temperature (Sec. III)], the energy loss due to electron-hole pair creation is an important thermalization process. If the energy is lower than this threshold, electron-hole pair creation becomes impossible and the thermalization is dominated by other processes, namely the creation of optical phonons[7,26] and—in highly p-doped crystals like we use—by

scattering at valence-band holes with simultaneous excitation of the holes.[26,27]

If electron-hole pairs are created, the excited crystal electrons strongly change the polarization of the conduction-band electrons. Especially at high energies of the incoming electrons, the large number of unpolarized excited electrons leads to a strong dilution of the initial electron polarization and consequently to a very small circular polarization of the emitted light. Therefore, the degree of electron polarization at the instant of recombination, P_r, determined from Eq. (2), is only a lower limit of the polarization which the incoming electrons alone retain before they recombine. An exact determination of the depolarization of the incoming electrons is only possible if the initial kinetic energy of these electrons is lower than the minimal band-gap value E_g.

Such low energies can only be achieved by lowering of the target work function. Without lowering (see Fig. 1), electrons which are brought to the kinetic energy E_{vac} in vacuum by applying the potential difference V_a between source and target, are accelerated to the higher energy E_0, called initial kinetic energy, in the conduction band of the target crystal, as an effect of the work function ϕ_T, with

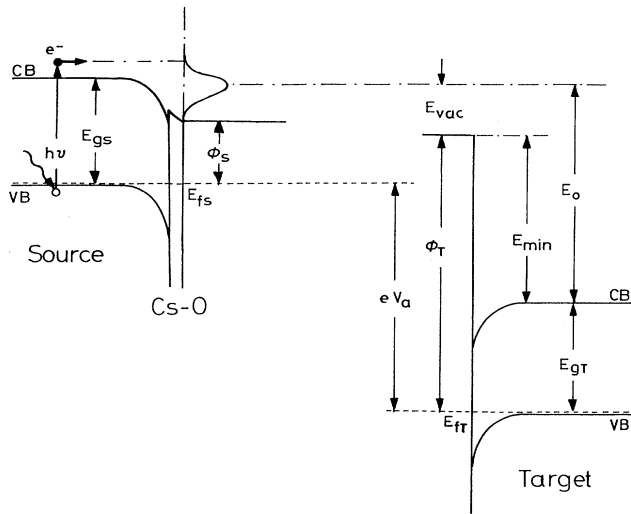$$E_0 = E_{vac} + (\phi_T - E_{gT}) , \qquad (3)$$

FIG. 1. Energy relations between source and target. *Source*: Electrons are excited from the valence (VB) to the conduction band (CB) by photons of an energy $h\nu$, which is only slightly higher than the minimal band gap E_{gs}. They can leave the source crystal because the work function ϕ_s is lowered below the value of the band gap in the crystal's bulk by depositing Cs and O. The energy distribution of the emitted electrons is idealized [see Drouhin *et al.* (Ref. 26) or Kirschner *et al.* (Ref. 28) for real distributions]. *Target*: If the mean kinetic electron energy in vacuum, just before entering the target crystal is E_{vac}, the electrons are accelerated to the higher energy E_0 in the conduction band of the target. This is an effect of the work function ϕ_T, which was not lowered in our experiment. (Further explanations in the text.)

where E_{gT} is the band gap of the target. Even if the electrons are totally decelerated in vacuum ($E_{vac}=0$), the minimal initial kinetic energy which can be achieved in the conduction band of the target crystal without lowering of the work function is

$$E_{min} = \phi_T - E_{gT} . \qquad (4)$$

With $\phi_T \approx 5$ eV [for clean GaAs (Ref. 29)] and $E_{gT} = 1.504$ eV for GaAs or $E_{gT} = 1.982$ eV for $GaAs_{0.62}P_{0.38}$, E_{min} is larger than 3 eV and therefore higher than E_{gT}, the threshold for electron-hole pair creation. With cesiation and oxidation of the target surface it is possible to achieve $\phi_T < E_{gT}$ and, consequently, no acceleration of the electrons into the target by means of the work function takes place. Then it is possible to obtain electrons of low kinetic energy $E_0 < E_{gT}$ inside the target by applying a suitable smaller voltage V_a: Electron-hole pair creation is avoided and the exact value of the depolarization of the injected conduction-band electrons due to spin-relaxation processes can be determined. Therefore, cesiation and oxidation is our next experimental aim.

C. Spin-relaxation processes

Polarized conduction-band electrons undergo various spin-relaxation processes until recombination occurs. The efficiency of these processes depends on crystal type, crystal temperature, degree of doping, and kinetic energy of the conduction-band electrons. In highly p-doped GaAs, two processes play the dominant role in spin relaxation. For "high"-energy electrons, i.e., *during* thermalization, the *D'Yakonov-Perel' process* (DP) is the main depolarization effect.[30,31] For thermal electrons, i.e., *after* thermalization, the *Bir-Aronov-Pikus process* (BAP) dominates the spin relaxation.[13,31,32]

(a) *The DP process* results from a spin-orbit splitting of the conduction band in III-V semiconductors: For wave vectors $\mathbf{k} \neq 0$ and specific directions the degeneracy of the conduction band is completely removed and, consequently, electrons of the same wave vector $\mathbf{k}$ but opposite spin directions have different energy. Then the Hamiltonian for an electron in the conduction band contains a spin- and wave-vector-dependent term which corresponds in form to the term for the potential energy of a free electron arising from its magnetic moment μ in a magnetic field $\mathbf{B}$. Therefore, it is customary to talk about a D'Yakonov-Perel' field[33] in the crystal as if it were some kind of "internal magnetic field" affecting the electron spins. One can compute a precession frequency Ω in analogy to the Larmor frequency. Here, however, Ω depends on magnitude and direction of the wave vector $\mathbf{k}$: The spins of electrons with different wave vectors are rotated by different amounts in different directions. This leads to a depolarization of the conduction-band electrons. Since Ω increases with increasing $\mathbf{k}$ (Refs. 31 and 34) the depolarization is more effective at higher electron energies.

It has to be noted that there are neither measurements

nor estimates published about the efficiency of the DP process in GaAs for electrons in the "high"-energy range we use and none at all for $GaAs_{1-x}P_x$. One can argue that the DP process is more efficient in GaAs than in $GaAs_{1-x}P_x$: Near the Γ point, the precession frequency Ω is given by[30-32,34]

$$\Omega = \alpha\hbar^2(2m_e^3 E_g)^{-1/2}\kappa ,\tag{5}$$

where m_e is the effective mass of the conduction-band electrons at the Γ point, E_g the minimal band gap, and α the so-called "splitting parameter." The vector κ depends on the wave vector of a considered conduction-band electron, because $\kappa_x = k_x(k_y^2 - k_z^2)$ (other components by cyclic change of k_x, k_y, and k_z). Under the assumption that α is of similar size in GaAs and $GaAs_{0.62}P_{0.38}$, which is the case, for example, for GaAs and GaSb (Refs. 32 and 35), the magnitude of Ω in $GaAs_{0.62}P_{0.38}$ is about one-half of the magnitude of Ω in GaAs because of the difference in E_g and m_e (for values for E_g, see Sec. II B; for m_e, see Aronov et al.[32] for GaAs and Craford et al.[36] for $GaAs_{1-x}P_x$). Therefore, the spins of electrons with the same wave vector might be rotated faster in GaAs than in $GaAs_{0.62}P_{0.38}$, resulting in a higher depolarization in GaAs.

(b) The *BAP process*, which dominates the depolarization of thermal electrons in highly p-doped crystals, is caused by the scattering of electrons at valence-band holes with simultaneous spin flip. Its efficiency increases with increasing degree of doping and with crystal temperature. From the results of photoluminescence experiments,[32] one can conclude for a GaAs crystal with $N_A = 2 \times 10^{19}$ atoms/cm^3 at $T = 90$ K, like we use (Sec. III), that the BAP processes reduces the polarization of the thermalized electrons by a factor of approximately $\frac{1}{2}$ until recombination occurs. For $GaAs_{1-x}P_x$ no photoluminescence data are available.

III. EXPERIMENTAL ARRANGEMENT

A schematic sketch of the experimental arrangement is shown in Fig. 2. To generate the polarized electrons, we use a $GaAs_{1-x}P_x$ source which was built following the design of the SLAC source.[37] The photocathode, a $GaAs_{0.60}P_{0.40}$ crystal p doped with more than 5×10^{18} atoms/cm^3 Zn, is cesiated and oxidized according to standard procedures.[4] The crystal is illuminated by the 647.1-nm line of a krypton-ion laser. The photon energy of 1.916 eV lies close to the room-temperature band gap of the crystal.[14] The linear polarized laser beam is circularly polarized by a quarter-wave plate and falls perpendicularly on the (100) surface of the crystal.

The emitted electrons move antiparallel to the laser beam. They are longitudinally polarized in or against the propagation direction of the light. In an electrostatic 90° deflection the electron and the laser beam are separated and the longitudinal polarization is transformed to a transverse one. In a solenoid the electron spin can be rotated by Larmor precession around the beam direction. After rotating by 90° and a second electrostatic 90°, deflection, the now again longitudinally polarized elec-
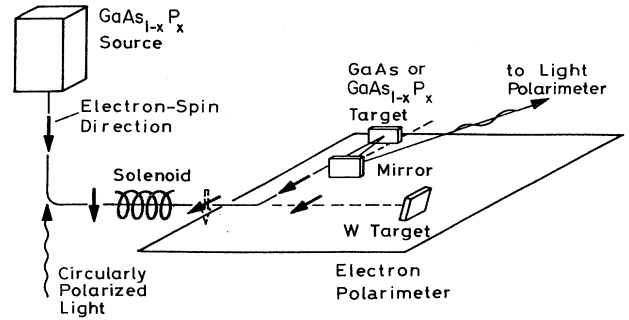

FIG. 2. Schematic diagram of the experimental arrangement.

trons impinge perpendicularly on the target.

As targets we use highly p-doped GaAs or $GaAs_{0.62}P_{0.38}$ samples. The acceptor concentration of the GaAs crystal is 2×10^{19} atoms/cm^3; that of the $GaAs_{0.62}P_{0.38}$ crystal is 4×10^{19} atoms/cm^3. The surface of both crystals is (100) oriented. The target crystal can be heated to more than 600 °C, the temperature used for cleaning GaAs and $GaAs_{1-x}P_x$. Heating is done before each sequence of measurements. The target can be cooled with liquid nitrogen; the temperature achieved thereby is 90 K.

The emitted light is observed under a mean angle of 25° with respect to the target normal, corresponding to $\phi \approx 7°$ in Eq. (1) after correction for the refraction at the surface. The light is then reflected by a plane mirror and passes through a window of the vacuum chamber into the light polarimeter, consisting of an achromatic quarter-wave plate, a Glan-Thompson polarizer, and an interference filter. The photons are detected by a photomultiplier with a cooled GaAs cathode which has a dark counting rate of 5–6 counts/s so that a very low light intensity can be measured. To determine the spectral distribution of the emitted light, a set of interference filters with half-widths of 5–9 nm and transmissions of 18–54 % is used.

Corrections to the measured circular polarization of the emitted light due to the refraction at the target surface and the reflection at the mirror surface were calculated and found, apart from the phase change of π in reflection, to be negligibly small.

When the electric field in the second beam bend is turned off, the transversely polarized electron beam goes straight into an absorbed-current electron polarimeter with a tungsten crystal as target. The electrons impinge on the W(100) surface under the fixed mean angle of 14° to the surface normal. We determine the degree of electron polarization by application of the zero crossing method.[38]

In our previous publication[23] we stated 15(3)% as electron polarization. This value was determined by using the value for the difference of the zero-intercept energies $\Delta = 4.1$ eV, given by Celotta et al.[39] for tungsten. A recent calibration of our absorbed-current polarimeter with an electron beam of known polarization gave $\Delta = 1.66$ eV and therefore an electron polarization of 38%. Presumably, the disagreement with Celotta et al.[39] stems from different crystal conditioning.

IV. RESULTS AND DISCUSSION

A. Spectral distribution

The spectral distributions of the emitted light resulting from electron impact are shown in Fig. 3 for $GaAs_{0.62}P_{0.38}$ at 90 and 300 K crystal temperature and in Fig. 4 for $GaAs_{0.62}P_{0.38}$ and GaAs at 90 K. The distributions are dominated by a high emission peak. The peak position occurs at an energy close to the minimal band gap of the crystal, independent of the kinetic energy of the incident electrons. Therefore, even at high energies the electrons are thermalized into the Γ minimum before they recombine with holes of the $P_{3/2}$ valence band. Transitions to other valence subbands or from higher states of the conduction band are not seen.

The peak shifts to higher energy with decreasing temperature as a consequence of the increasing band gap,[24,40] as shown in Fig. 3. Figure 4 shows the shift of the peak position due to the variation of the band gap with phosphorus concentration.[14,41-43]

It should be noted that the emission-peak position varies with the acceptor concentration of the crystals as a consequence of acceptor-band formation[44,45] and shrinkage of the band gap.[46-48] The peak position of the emitted light from our highly p-doped GaAs sample (Sec. III) is in good agreement with the peak positions in cathodoluminescence[49] and photoluminescence experiments[50,51] for GaAs of the same acceptor concentration at 77 K crystal temperature. Data for $GaAs_{1-x}P_x$ are not available.

FIG. 4. Spectral distributions of the light emitted from $GaAs_{0.62}P_{0.38}$ (same as in Fig. 3) and GaAs at 90 K crystal temperature. The initial kinetic energy of the electrons is $E_0 = 1000$ eV.

The emission spectrum of $GaAs_{0.62}P_{0.38}$ at 90 K shows a broad secondary maximum at energies smaller than the minimal band gap. Such maxima are observed in GaAs, $GaAs_{1-x}P_x$, and GaP in cathodo-, photo-, and electroluminescence experiments.[52-55] They are assigned to transitions from the conduction band into deep impurity levels or from deep impurity levels to the valence band. Such impurities are brought into the crystal in the production or the doping process.

The light intensity decreases with decreasing electron energy because the number of excited crystal electrons and therefore the total number of recombining electrons decreases. In addition, the light intensity decreases with increasing temperature (Fig. 3). This fact is well known from photoluminescence experiments.[47,56] It is explained by an increasing probability for radiationless recombination with increasing temperature. Microscopic defects or inclusions can form a continuum of states between conduction and valence bands. They can be surrounded by potential barriers. Only hot carriers with sufficient energy to overcome the barrier can recombine nonradiatively via the interband states. Increasing the temperature will then increase the number of nonradiative transitions.[45]

B. Circular polarization

The circular polarization of the recombination radiation was measured for each crystal at the emission maximum at 90 K crystal temperature (Fig. 4). At 300 K, the light intensity was too low, especially at low electron energies.

For the elimination of apparative asymmetries we reverse the electron polarization at the $GaAs_{1-x}P_x$ source,
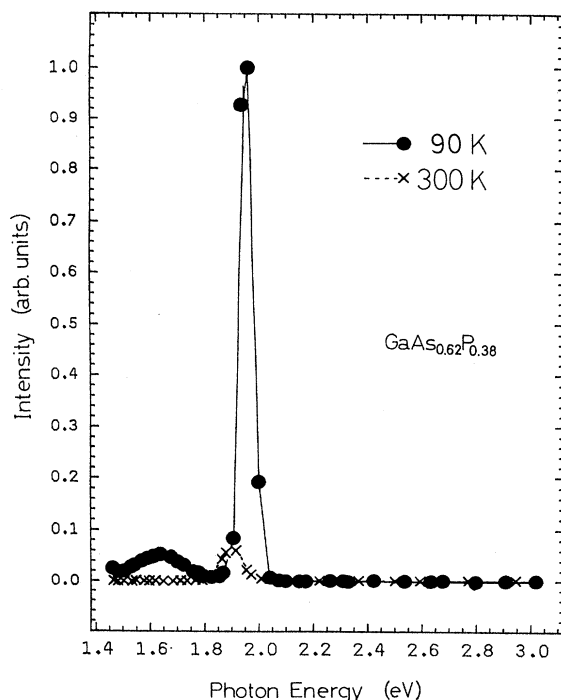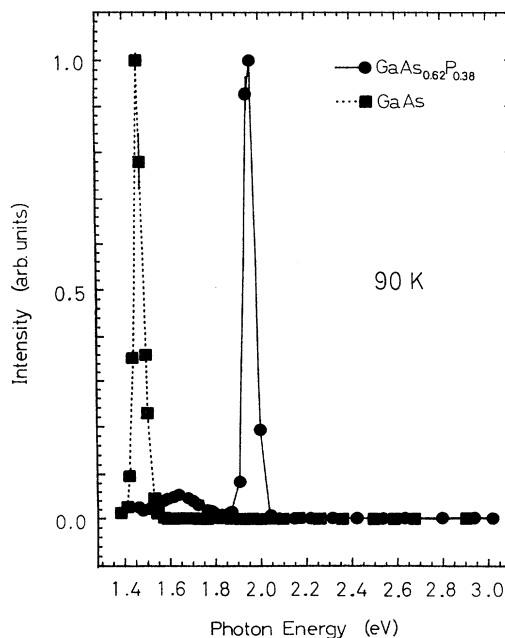

FIG. 3. Spectral distributions of the light emitted from $GaAs_{0.62}P_{0.38}$ at 90 and 300 K crystal temperature. The initial kinetic energy of the electrons is $E_0 = 1000$ eV.

simply by reversing the sign of the circular polarization of the exciting light. An additional check is provided by the reversal of the magnetic field in the solenoid, which results in a reversal of electron polarization at the target and, therefore, a sign change of the circular polarization of the emitted light. If the magnetic field in the solenoid is turned off, the electrons are transversely polarized at the target and no circular polarization of the emitted light is expected in our direction of observation [cf. Eq. (1)]. Our measurements of the circular polarization P_{circ} of the emitted light as a function of the initial kinetic energy E_0 of the electrons show the predicted dependence on the magnetic field in the solenoid, as can be seen in Fig. 5 for the $GaAs_{0.62}P_{0.38}$ sample.

Figure 6 shows the absolute value of the circular polarization $|P_{circ}|$ of the recombination radiation for the $GaAs_{0.62}P_{0.38}$ and the GaAs sample. The data from the measurements with both magnetic field directions in the solenoid are combined. The circular polarization is very small, as expected at these relative high kinetic energies of the electrons, where electron-hole pair production in the crystal reduces the degree of electron polarization in the conduction band (Sec. II B). The polarization is below 1% in the whole energy range for both crystals and decreases with increasing energy because of the increasing number of electrons excited into the conduction band by the electron-hole pair production. It is surprising that at the high energy of 100 eV a small but measureable degree of polarization still remains. The extremely low sig-
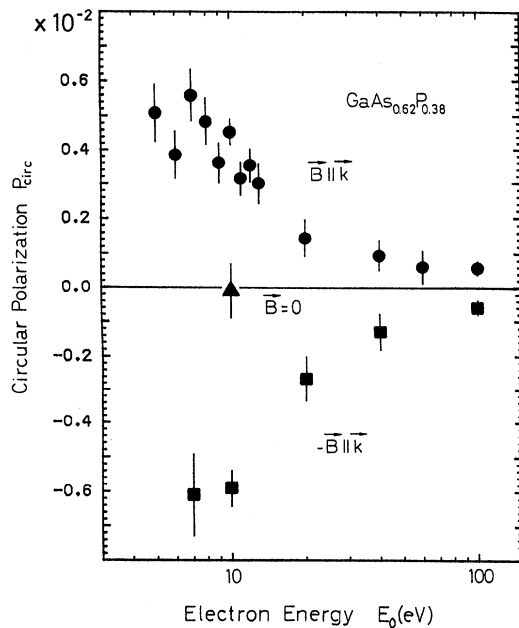

FIG. 6. Circular polarization $|P_{circ}|$ of the emitted light from GaAs and $GaAs_{0.62}P_{0.38}$ as a function of the initial kinetic energy E_0 of the injected electrons.

nal rate prevented smaller statistical errors. For each polarization value several days of data taking were needed. The value at 10 eV, for example, is the result of measurements of 8–12 h on 16 days; the average counting rate was 160 s^{-1}.

The measured polarization for the GaAs crystal is much lower than that for $GaAs_{0.62}P_{0.38}$. This significant difference cannot only be explained by the creation of a slightly higher number of electron-hole pairs in GaAs because of the lower minimal band gap (Sec. II B). Therefore, it has to be assigned to a more efficient depolarization of the conduction-band electrons.

The examined crystals had previously been used in our GaAs/$GaAs_{1-x}P_x$ source and for both crystals electron polarizations of the same order, more than 30%, were obtained. From this fact we conclude, that the depolarization of *thermal* electrons (which is responsible for the reduction of the polarization of the emitted electrons from the sources), is of similar size for both crystals. This leads to the conclusion that the depolarization *during* thermalization is higher in GaAs than in $GaAs_{0.62}P_{0.38}$. This result, which has to be substantiated by further measurements with other cyrstals and at lower electron energies, might support the assumption (Sec. II C) that the D'Yakonov-Perel' process is more efficient in GaAs.

FIG. 5. Circular polarization, P_{circ}, measured in the emission maximum of the recombination radiation from $GaAs_{0.62}P_{0.38}$ ($T=90$ K), as a function of the initial kinetic energy E_0 of the electrons. Two different directions of the magnetic field in the solenoid (shown in Fig. 2) were used: parallel (●) and antiparallel (■) to the electron momentum k in the solenoid. Without magnetic field (▲), the electrons impinge transversely polarized onto the target.
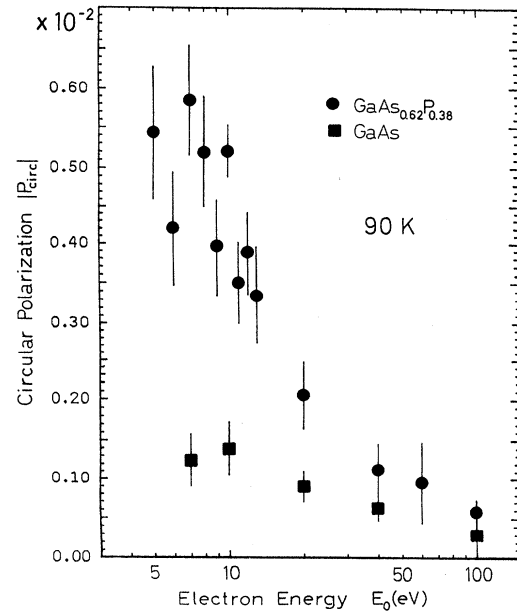
V. SUMMARY

We performed the first low-energy cathodoluminescence experiment with polarized electrons and determined the circular polarization of the recombination radiation as function of the electron energy for GaAs and $GaAs_{0.62}P_{0.38}$. Contrary to expectations based on photoluminescence results, the circular polarization is measurable, albeit small.

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