Precession of the Spin Polarization of Photoexcited Conduction Electrons in the Band-Bending Region of GaAs(110)

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A precession of the conduction-electron spin polarization $\vec{P}$ away from the initial direction defined by the direction of the circularly polarized pumping light beam is found in photoemission experiments from GaAs(110)/(Cs,O). This precession occurs in the band-bending region about specific crystallographic directions and arises from the spin-orbit–induced spin splitting of the conduction band. These findings open new possibilities for the investigation of the electronic properties of this important interface region.

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Negative- (and positive-) electron-affinity GaAs and related semiconductor compounds photoemit spin-polarized electrons when irradiated with circularly polarized light.[1] A working description of the photoemission process in negative-electron-affinity (NEA) photocathodes is provided by the "three step" model, i.e., optical excitation of electrons into the conduction band, transport of the excited electron to the surface, and escape of the electron across the surface into the vacuum.[2] In order to achieve an efficient emission of the optically oriented electrons into vacuum, the electron affinity at the surface of heavily doped p-type GaAs is lowered by deposition of Cs and O_2. Thereby a surface depletion zone is created and consequently there is a *downward* bending of the bands at the surface. Possible changes of the spin polarization $\vec{P}$ of the excited photocarriers during electron transport through this region has not been investigated experimentally up to now. So far only a theoretical analysis by two of the present authors[3] has pointed out, in a qualitative way, the existence of spin-orbit–induced changes (precession) of $\vec{P}$ in the band-bending region.

We report in this Letter the first observation of such a spin-polarization precession in GaAs and discuss its origin in relation to the electronic structure of the conduction band of this material in the band-bending region. The physical effect we want to investigate can be illustrated in the following way: Conduction electrons moving from the bulk into the band-bending region gain kinetic energies of at least a few tenths of an electronvolt before escaping into the vacuum. When considering electrons with such high kinetic energy it is necessary to take into account the *spin splitting of the conduction band* due to the spin-orbit interaction in conjunction with the lack of inversion symmetry in III-V compounds. This splitting is described by the Hamiltonian

$$H_\Omega = \hbar(\vec{\sigma}\cdot\vec{\Omega})/2, \tag{1}$$

where $\vec{\sigma}$ are the Pauli spin matrices and

$$\hbar\vec{\Omega} = 2\gamma\vec{\kappa}, \tag{2}$$

where $2\gamma = \alpha\hbar^3(2m_{\rm eff}^3E_g)^{-1/2}$; $m_{\rm eff}$ is the effective mass; $\vec{\kappa}$ is a vector with components $\kappa_x = k_x \times (k_y^2 - k_z^2)$, $\kappa_y = k_y(k_z^2 - k_x^2)$; $\kappa_z = k_z(k_x^2 - k_y^2)$; E_g is the width of the forbidden gap (1.42 eV at room temperature for GaAs); α is a dimensionless coefficient; and $\vec{k}$ is the electron wave vector.[4]

This conduction-band splitting is equivalent to the existence of an effective magnetic field $\vec{B}_{\rm int}$ (parallel to $\vec{\kappa}$) experienced by the magnetic moment of the electron. The magnitude and direction of $\vec{B}_{\rm int}$ depend on the magnitude and direction of the wave vector of the photoelectron. We point out that in the bulk, electron scattering leads to momentum changes resulting in a *random* variation of magnitude and orientation of this effective magnetic field. The spin precession in such a randomly varying field was shown to cause *depolarization* of conduction electrons.[5,6] In the band-bending region this effective magnetic field can, however, play a very different role. For very small band-bending widths, electrons gaining high kinetic energy can

pass this region *ballistically with* $\vec{k}$ *normal to the surface.* Therefore, the direction of the effective magnetic field will be the same *for all* escaping electrons. As a result the photoelectron polarization vector $\vec{P}$ will be *rotated* away from the initial direction defined by the pumping light beam. For GaAs, according to Eq. (2), this rotation should be maximal for $\vec{k}$ in $\langle 110\rangle$ directions and zero for $\vec{k}$ in $\langle 100\rangle$ or $\langle 111\rangle$ directions. For $\vec{k} \parallel [110]$ the precession should occur about the $[1\bar{1}0]$ axis. For this case Fig. 1 illustrates the relative orientation of the vector $\vec{\Omega}$ with respect to the crystal axes as well as the experimental arrangement used to detect the precession of the spin polarization $\vec{P}$.

Preparation of the photocathode and spin-polarized photoemission experiments were performed in an apparatus described elsewhere.[7] The only novel feature is a solenoid S (see Fig. 1) inserted in the path of the electron beam[8] so as to detect the rotation of the spin polarization vector. The polarization in vacuum is determined by Mott scattering which is sensitive to the projection $P_v = |\vec{P}|\cos(\theta + \theta_p)$ where θ_p is the precession angle in the GaAs(110) band-bending region and θ the rotation (precession) angle caused by the uniform external magnetic field $\vec{B}_{ext}$ of the solenoid.

Figure 2 shows P_v vs θ measurements performed on a NEA GaAs(110) (Zn-doped, $N_A = 1.2\times 10^{-19}$ cm^3) crystal oriented with the $[1\bar{1}0]$ direction parallel to the external magnetic field. For negative as well as for near-zero electron affinities the same precession angle $\theta_p = 14 \pm 2°$ was measured at photon energies $\hbar\omega = 1.43$ and 1.65 eV. The direction of the rotation was such that $\vec{P}$ was turned towards the [001] direction, i.e., clockwise about the $[1\bar{1}0]$ direction, as drawn in Fig. 1. The distinction between the [110] and $[1\bar{1}0]$ directions[9] was done by preferential etching with HNO_3.[10] Rotation of the crystal by an angle of 180° about the surface normal changes the sign of θ_p but leaves the magnitude unchanged. This is expected because this operation is equivalent to a reversal of the sign of $\vec{B}_{int}$ in the laboratory frame of reference. Furthermore in the case where the $[1\bar{1}0]$ direction is perpendicular to $\vec{B}_{ext}$, i.e., $[001] \parallel \vec{B}_{ext}$, the P_v vs θ curve is symmetric (see Fig. 2), i.e., there is no spin precession about $\langle 100\rangle$ crystal axes, in agreement with the predictions of Eq. (2). We also checked that $\vec{B}_{int} = 0$ for $\vec{k}$ parallel to a $\langle 100\rangle$ direction. For this purpose measurements were performed on a GaAs(100) surface. In this case no precession was found, within the experimental ac-

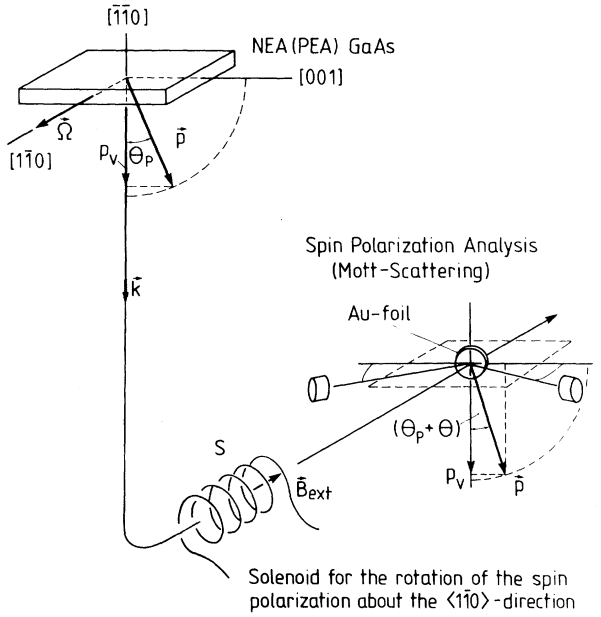

FIG. 1. Principle of the experiment: The longitudinally polarized electron beam from the GaAs(110)/(Cs,O) photocathode is deflected by 90° (giving transverse polarization) before passing through the solenoid (external magnetic field) and reaching the spin analyzer (Mott scattering).

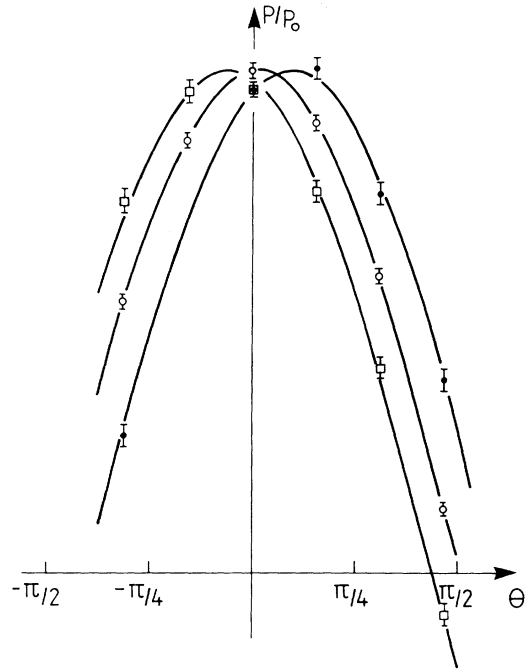

FIG. 2. Spin polarization P_v vs rotation angle θ for three different orientations of the $[1\bar{1}0]$ direction of the crystal with respect to the axis of the solenoid (external magnetic field $\vec{B}_{ext}$). Squares, $[1\bar{1}0]$ oriented in the apparatus as shown in Fig. 1; closed circles, after crystal rotation by 180° about [110]; open circles, $[1\bar{1}0] \perp B_{ext}$.

curacy of $\pm 1°$. Measurements performed on positive-electron-affinity (PEA) GaAs(110) yield higher precession angles, of up to 23°, for photon energies of the pumping light in the range $1.9 \leq \hbar\omega \leq 2.2$ eV.

The spin-orbit–induced rotation of conduction-electron spin in the band-bending region is related to the electronic properties of the crystal in the following way: The precession angle is

$$\theta_p = \int_0^\tau |\vec{\Omega}| \, dt, \tag{3}$$

where τ is the electron flight time. If we assume parabolic band bending the ballistic electron kinetic energy is $E(x) = \delta(x/L - 1)^2$ where δ is the energy of the band bending and x the space coordinate with the origin at the surface. For simplicity we assume that thermalized electrons are injected into the band-bending region (at $x = L$) and that their thermal energy is negligible compared with δ. Experimentally this is realized in photoemission from NEA or near-zero electron-affinity materials, for photon energies very near E_g. Making the change of variables $d\hbar k = (dE/dx)dt = [2(\delta E)^{1/2}/L]dt$, where $k = |\vec{k}|$, then, since $L = (2\epsilon\epsilon_0\delta/N_A e^2)^{1/2}$,[11] one has (in mks units)

$$\theta_p = \frac{1}{e}\left(\frac{\epsilon\epsilon_0}{2N_A}\right)^{1/2} \int_{k_0}^{k_\delta} \frac{\hbar|\vec{\Omega}|}{E^{1/2}(k)} dk, \tag{4}$$

with $k_0 = 0$ and k_δ the electron wave vector at $x = L$ and $x = 0$, respectively, and θ_p in radians. For $\vec{k} \parallel [110]$ it follows, from Eq. (2), that $\hbar|\vec{\Omega}| = k^3$. This is valid, however, only very close to the Γ point. For large quasimomentum Refs. 12–14 show that higher-order terms in k are needed. Therefore, for the calculation of the precession angle in Eq. (4) we used the numerical results for $\hbar\vec{\Omega}$ given in Ref. 13. $E(k)$ is taken from Ref. 14 up to $k = 0.1$ Å^{-1} and from Fig. 7 of Chelikowsky and Cohen,[15] slightly modifed for matching, in the range $k > 0.1$ Å^{-1}. Thus Eq. (4) yields $\theta_p = 14°$ for $k_\delta = 0.22$ Å^{-1} which corresponds to a band bending $\delta = 1 \pm 0.1$ eV. The fact that this value is higher than the band bendings of 0.5–0.7 eV found by other authors[16,17] could be due to too small values for the conduction-band splitting used in our calculations. To given some feeling of the accuracy of the present method we note that with $k_\delta = 0.16$ Å^{-1}, consistent with a band bending of 0.7 eV, Eq. (4) yields $\theta_p = 8°$. We find that the sense of the rotation is in agreement with theory.[13] Furthermore it must be seen as a sign of reliability that the coefficient of the k^3 term determined in Refs. 13 and 14 is in rather good agreement with the value of $\gamma = 22$ eV Å^{-3} which was recently determined in studies of the spin relaxation of thermalized electrons in bulk GaAs at 77 K.[6]

It is interesting to note that the rotation angle does not change noticeably when the electron affinity increases from NEA to PEA. This might indicate that near the NEA/PEA crossover the band bending is not significantly changed with the increase of the electron affinity. On the other hand for PEA GaAs(110) the increase of photon excitation energy results in a strong increase of the rotation angle θ_p. This can be qualitatively understood by the strong dependence of the conduction-band splitting with increasing k. The results presented show, in good agreement with theory, that the observed spin-orbit–induced spin-polarized precession θ_p is intimately related to the symmetry and k dependence of the electronic structure of the conduction band of the semiconductor in the band-bending region. We note that the magnitude of θ_p is also governed by the band-bending-region parameters of the semiconductor, i.e., doping level, band bending, and depth of the depletion zone.

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