Diagnostic of semiconductor device structures by spin-labeled electrons

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Abstract. The influence of non-uniform distribution of spin density in the temperature range from 5 to 80 K under the conditions of optical orientation of electrons in semiconductors is analyzed. Possibility to determine the kinetic parameters of carriers by depolarization of recombination radiation in a magnetic field is shown. Electron diffusion length and mobility is defined for materials with a hole conductivity. An estimated value of the rate of recombination on a free surface and its influence on the distribution of the concentration of non-equilibrium electrons from the excitation surface into the bulk is presented.

1. Introduction

The first experiments on optical orientation in direct band gap semiconductors [1, 2] allowed for determination of the lifetime of minority carriers preferential spin orientation. Most of the findings were obtained under steady-state conditions for bulk III-V crystals and solid solutions based on gallium arsenide.

Results of theoretical studies of spin relaxation mechanisms, propped by experimental work, are collected in the review book [3]. To better demonstrate the role of mechanisms of spin relaxation in the actual experimental conditions were not taken into account, which were cast aside as an insignificant correction.

The edge luminescence of the active layer of GaAs photocathodes with hole conductivity [4, 5, 6] and active layer of semiconductor laser diode structures [7] was studied in detail.

In this paper we investigated polarized luminescence from layers of AlGaAs structures with different manufacturing technologies: GaAs photocatodes buffer layer and the AlGaAs laser diode heterostructure.

2. Samples and experimental procedure

The experiments were carried out in the temperature range from 5 to 80 K, where, at low-temperature, we deal with localized carriers. As the temperature increases, the carrier mobility reaches its maximum value [8] and the diffusion transport of carriers should manifest itself. Investigated layers had thickness $d$ of the order of magnitude of the diffusion length of the nonequilibrium carriers $L_e$ (thin) and substantially exceeding it ($d \gg L_e$) (thick). Layers of p-type Al$_{0.3}$Ga$_{0.7}$As with doping concentrations $p \sim 10^{16} \text{ cm}^{-3}$ and thickness $d \approx 2 \mu\text{m}$ and $d \approx 20 \mu\text{m}$ were grown on GaAs substrates (Fig. 1(a) and (b)). The effect of optical orientation of electrons was observed in reflection geometry. Sample was excited by a circularly polarized light from a He-Ne laser. The degree of circular polarization $\rho$ was measured using the...
photoelastic modulator and a linear polarizer with synchronous counting of left and right-hand polarized photons.

3. Results
The lifetimes of electrons $\tau$ and of the preferential orientation of the spin of minority carriers $T_s$ are related to the photoluminescence (PL) polarization degree and the half-width of PL depolarization curve in a magnetic field given by:

$$\tau = \frac{0.25}{\rho} \cdot T_s$$
$$T_s = \frac{h}{g\mu} \cdot \frac{1}{\Delta B}$$

where $\rho$ is the degree of circular polarization, $g$ is the electron g-factor in the conduction band, $\mu$ is the Bohr magneton, $h$ is the Planck constant and $\Delta B$ is a magnetic field at which the degree of PL polarization decreases twice from its original value.

Noticeable difference is observed in how the PL polarization degree and spin lifetime $T_s$ changes with increasing temperature. At low temperature, $T = 5$ K, the half-width of the PL depolarization curves for both $p$-AlGaAs are approximately the same (Fig. 1). Nonetheless, broadening of the PL depolarization curve for a thin layer is evident with the temperature rise. When increasing the temperature to 80 K, the half-width ratio is $\Delta B_{T=80K}/\Delta B_{T=5K} \approx 30$ for thin (Fig. 1(a)) and $\Delta B_{T=80K}/\Delta B_{T=5K} \approx 2.7$ (Fig. 1(b)) for thick $p$-AlGaAs sample.

Values for $\tau$ and $T_s$ determined from the experiment for a thin ($d \approx 2\mu m$) and thick ($d \approx 20\mu m$) sample at two temperatures $T = 5$ K and $T = 80$ K are given in Table 1. The value of the electron g-factor, $g = 0.41$, for Al$_{0.3}$Ga$_{0.7}$As is taken from Ref. [9].

In thin structure (Fig. 1(a)), the entire thickness of the AlGaAs layer is subjected to the photoexcitation. Difference in the electron energy in the AlGaAs layer and the GaAs substrate leads to the energy relaxation of electrons at the heterojunction to substrate. A diffusion flux is created in the direction of the heterojunction. The increase in the polarization degree to the limiting values and the broadening of the depolarization curves in a magnetic field with increasing temperature is explained by a decrease of the electron lifetime. Under the condition

**Figure 1.** The PL depolarization curves in a magnetic field and the space-energy structure of (a) thin and (b) thick sample. Circles correspond to measurements at $T = 80$ K and triangles at $T = 5$ K.
Table 1. \( \tau \) and \( \tau_s \) for thin and thick sample.

| \( d \) (\( \mu m \)) | \( \tau \) (ns) | \( \tau_s \) (ns) |
|----------------|-------------|-------------|
| 2             | 7.0 (5K)    | 0.2 (80K)   |
| 20            | 4.9 (5K)    | 4.4 (80K)   |

\( d < \alpha^{-1} \), where \( \alpha \) is the absorption coefficient of substance in the spectral region of PL (in our case for \( d = 2 \mu m, \alpha = 3 \cdot 10^4 \text{ cm}^{-1} [10] \)) it is valid to assume that the excitation intensity is the same over the entire thickness of the layer: \( g_0 \approx \alpha \cdot I_0 \), where \( g_0 \) is the generation rate of carriers. Then, the diffusion equation is:

\[
D \cdot \frac{d^2 n(z)}{dz^2} - \frac{n(z)}{\tau} + g_0 = 0. \tag{2}
\]

Here \( D \) is the carrier diffusion coefficient, and \( z \) is the distance from the surface. The rate of surface recombination can be assumed to be negligibly small [6] while the rate of disappearance of electrons at the heterojunction infinitely large. The solution of equation (2) will then be:

\[
n_z = g_0 \cdot \tau + A \cdot \exp(\lambda \cdot d) + \exp(-\lambda \cdot d), \tag{3}
\]

where \( A = \frac{g_0 \cdot \tau}{\exp(\lambda \cdot d) + \exp(-\lambda \cdot d)} \) and \( \lambda = \frac{1}{\sqrt{D \cdot \tau}} = \frac{1}{L_e} \), \( L_e \) is the electron diffusion length.

This makes it possible to find the effective lifetime of nonequilibrium carriers in the layer, as the average lifetime:

\[
\bar{\tau} = \frac{1}{d} \int_0^d \frac{n_z}{g_0} \, dz = \tau \cdot \left( 1 - \frac{L_e}{d} \cdot \frac{\exp(2 \cdot d/L_e) - 1}{\exp(2 \cdot d/L_e) + 1} \right). \tag{4}
\]

The carrier lifetimes in the bulk material \( \tau \) were taken from experiments on a thick \((d >> L_e)\) sample.

Figure 2. Dependence of the concentration distribution of photoexcited carriers in the layer on distance from the free surface for different values of the diffusion length.

Comparing the calculated lifetime \( \tau \) with the experimentally determined one, we can determine the diffusion length of the electrons and diffusion coefficient. For temperature \( T = 80 \) K, the best agreement with experiment is achieved when \( L_e = 13.8 \) \( \mu m \), which corresponds to \( D = 240 \) cm\(^2\)/s. Using the Einstein relation, one can estimate the mobility...
of electrons $\mu_e = 21500$ cm$^2$/V·s, i.e. the mobility of the minority carriers is experimentally determined.

Taking into account the dependence of the mobility $\mu$ on the temperature reported in Ref. \[8\] and exploiting the Einstein relation, we calculated $\bar{\tau}$, the degree of PL polarization, for the whole temperature range of interest (Fig. 3).

We used the approach realized in Ref. \[5, 6\] to estimate the rate of surface recombination. Analysis of diffusion in a semi-infinite sample makes it possible to calculate the increase in the half-width of the depolarization curve as a function of the rate of surface recombination. The results of such calculations for several values of the diffusion coefficient $D$ are given in Fig. 4.

The diffusion coefficient $D \approx 240$ cm$^2$/s is taken from our experiments. Dependencies for other values are given for comparison and illustration of the scale of possible changes of the spin lifetime, influenced by the surface recombination. With an increase in the surface recombination rate $T_S$ decreases as a result of the loss of carriers on the surface, however, at high surface recombination rates $\eta$, the spin lifetime tends to a constant value, which is determined by the diffusion coefficient of the electrons.

**Figure 3.** Dependence of the PL polarization degree for a thin layer, $d = 2$ µm, and the lifetime of electrons on temperature. Solid lines are calculation.

**Figure 4.** Calculation of the effect of surface recombination on the lifetime of spin $T_S$ in semi-infinite sample with different diffusion coefficients. Points on the figure corresponds to the experimental data given in Table 2.
Rate of surface recombination and electron diffusion coefficient increase with temperature. From the comparison of \(T_S\) at the interface in considered temperature range, the rate of surface recombination at \(T = 80\) K can be predicted. Table 2 gives estimates of the rate of surface recombination performed on the basis of our data and published in the literature.

| Point number on the Fig.4 | \(T_S(77)/T_S(5)\) | \(\eta\) cm/s | Ref. |
|---------------------------|-------------------|--------------|-----|
| -                         | 0.97              | \(10^2 <\)   | [11]|
| -                         | 0.978             | \(10^2 <\)   | [12]Table 1, sample 4 |
| 1                         | 0.86              | \(4 \cdot 10^4\) | [12]Table 1, sample 1 |
| 2                         | 0.8               | \(8 \cdot 10^4\) | [13]|
| 1                         | 0.88              | \(2 \cdot 10^4\) | our data, Fig.4 |

Measuring the rate of depolarization in a transverse magnetic field in the buffer layer of the GaAs photocathode (Fig. 1(a)), we practically repeated the first study of diffusion transport of optically oriented (spin labeled) electrons at 77 K [14]. We have proved that the decrease in the spin lifetime \(T_S\) is related, not with recombination on a free (etched) surface, as claimed by the authors, but with the loss of electrons at the interface.

4. Conclusions

Introduction of experimental conditions and an adequate description of the processes of generation, relaxation, and transport of spin in the conditions of its non-equilibrium distribution can give us a tool for studying spin dynamics and diagnostics of the parameters of semiconductor device structures.

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