The Hanle Effect in Nonuniformly Doped GaAs

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Abstract—Spin density distribution in the GaAs/AlGaAs heterostructure was studied under steady-state optical orientation conditions. A comprehensive analysis of the dynamics and relaxation processes responsible for the steady-state nonuniformity of spin orientation was made. The acceptor impurity concentrations in various regions of nonuniformly doped gallium arsenide were determined. The concentrations were derived from the spin relaxation times measured using the optical orientation method. © 2003 MAIK “Nauka/Interperiodica”.

1. High hopes were pinned on the spin orientation in semiconductors as a phenomenon which could be potentially applied in the area of information recording, processing, and storage [1]. Recently, studies of spin phenomena in various materials, including semiconductors, have been attracting considerable interest. Record-long spin memory times of electrons in n-GaAs have been detected [2]. It has been shown that the spin relaxation time in p-GaAs exceeds the lifetime of photoexcited electrons [3] and that the decrease in orientation can be assigned to luminescence photon recycling. In gallium arsenide and the related heterostructures, the spin relaxation time can be controlled by properly varying the external magnetic field [4], doping level [2], electric field [5], and pump photon energy [6].

Controlling the electron spin as an information carrier is intimately connected with the nonuniform spin density distribution and spin transport. The nonuniformity in spin distribution also makes it possible to determine the kinetic recombination parameters and the mechanisms responsible for the transport of carriers and of their average spin [3]. It is appropriate to note here that the first observation of motion of nonequilibrium spins of optically oriented electrons was made in an experiment involving a heterogeneous structure. It was demonstrated that the spin orientation of electrons crossing the interface between a comparatively broad-to-a-narrow-band-gap semiconductor is preserved [7]. Later studies revealed a drift of spin-polarized electrons in variable band-gap structures [8].

The effects of the recombination conditions at the crystal surface and in the bulk on optical orientation in doped gallium arsenide were found to be inequivalent earlier in [9]. A study was made of the edge luminescence depolarization in a transverse magnetic field (the Hanle effect) and of the dependence of the depolarization rate on pump photon energy. The idea underlying the experiment was as follows. In GaAs, we deal with direct optical transitions and, hence, a high absorption coefficient α. Optical orientation is produced in a thin surface crystal layer whose effective thickness d ~ α−1 varies strongly with variation of the pump photon energy E_p. If the surface recombination velocity of electrons η is large enough (the η/d ratio is of the order of the reciprocal spin orientation lifetime T_s−1), it can be measured using the spin orientation effect. The half-width of the p(H) dependence was found to vary with pump photon energy at 77 K (p is the degree of luminescence circular polarization, H is a transverse magnetic field), and this was assigned to the effect of the spin relaxation rate and recombination velocity on the free GaAs surface [9, 10].

However, comprehensive studies of the kinetic parameters performed later on GaAs samples with the same doping level using various methods [3, 11] led to results that are in contradiction to the conclusion drawn in [9]; namely, it was found that surface recombination in p-GaAs at 77 K is very weak and should not affect the optical orientation noticeably.

This communication reports on additional experiments carried out on p-GaAs/AlGaAs heterostructures, including samples studied in [9], and reveals the reasons for the contradictory interpretation of the results of optical orientation experiments reported in [3, 11] and [9]. It is shown that the variation of the magnetic luminescence depolarization rate with pump photon energy is caused by the nonuniform distribution of the acceptor concentration across the p-GaAs layer in the structure studied in the first experiments [9].

The measurements reported in [11] were conducted in stationary conditions at room temperature and under high-frequency (26.6 kHz) modulation of the polarization and intensity of luminescence. This method of measuring the nonequilibrium-carrier diffusion length is based on the use of self-absorption, i.e., the absorp-
tion of the recombination radiation in the sample itself, which is a GaAs crystal in our case [12]. If the dependence of the absorption coefficient $\alpha$ on the wavelength of light $\lambda$ is known, the distribution of the nonequilibrium carrier concentration can be derived from the variation of the luminescence line shape.

When the crystal surface is illuminated by photons of energy $E_{ph} \geq E_g$, the spatial distribution of photoexcited carriers is determined primarily by their diffusion into the crystal bulk and recombination. The distribution of nonequilibrium carrier concentration in thin crystals (with thickness of the order of the electron diffusion length) depends on the recombination velocity at the surface opposite the illuminated side. The surface recombination velocity at the free $p$-GaAs surface ($p \sim 10^{18}$ cm$^{-3}$) is fairly high ($\eta_0 = 8 \times 10^8$ cm/s at $T = 300$ K [13]). It is known, however, that crystallization of the solid solution on the GaAs surface gives rise to passivation, a process in which the number of defects and states characteristic of the free GaAs surface decreases substantially [14], thus resulting in a decrease in the surface recombination velocity.

These effects in thin layers can be studied most conveniently from the spectral dependence of the intensity ratio of the luminescence leaving opposite sides of a plane-parallel sample, $I_1(\lambda)/I_2(\lambda)$. This ratio does not contain parameters capable of affecting the luminescence line shape, which facilitates analysis of the experimental data. The behavior of the $I_1(\lambda)/I_2(\lambda)$ dependence is governed by the $\alpha(\lambda)$ relation at the absorption edge and by the carrier spatial distribution in the crystal.

The study of the effect of the nonuniform distributions of electron concentration and spin density on optical orientation was carried out in three stages. In the first stage, measurements of the wavelength dependence of the absorption coefficient $\alpha$ for the GaAs layers of interest were performed in the edge luminescence region. In the second stage, the $I_1(\lambda)/I_2(\lambda)$ dependence was obtained and the $\alpha(\lambda)$ relation was used to determine the room-temperature recombination velocity at the free GaAs surface. It was also shown experimentally that the electron recombination at the free GaAs surface at 77 K is very small and cannot affect the electron concentration distribution away from the light-illuminated heterointerface into the bulk of the gallium arsenide crystal. In the third stage, experiments were carried out on the samples employed in [9]. We studied luminescence spectra and electron spin orientation in the reflection geometry. The results obtained in these experiments indicate that the doping is substantially nonuniform in the region close to the free GaAs surface.

2. Samples of the first group were inverted structures [15] similar to those used in the production of GaAs-based photocathodes. A 0.5-mm-thick layered structure $(n$-$\text{Al}_{0.6}\text{Ga}_{0.4}\text{As})/(p$-GaAs)/$(p$-$\text{Al}_{0.6}\text{Ga}_{0.4}\text{As})$ was grown through molecular beam epitaxy on a GaAs substrate. An 8-$\mu$m-thick $p$-GaAs active layer was doped by germanium to a level of $(3–5) \times 10^{18}$ cm$^{-3}$. A $p$-$\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ buffer layer 1–2 $\mu$m thick, doped by germanium to $(5–8) \times 10^{17}$ cm$^{-3}$, was capped by a 150- to 200-nm-thick SiO$_2$ layer. Next, this structure was welded through thermal compression with a glass having a thermal expansion coefficient close to that of gallium arsenide. After this, the substrate and the $n$-$\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ stopper layer were etched off chemically. Below, we present experimental data on two samples that differ only in the thickness of the $p$-GaAs layer (2.5 and 5 $\mu$m).

The parameters characterizing the spatial distribution of electrons in the GaAs layer were derived from the spectral dependence of the intensity ratio $I_u/I_{ref}(\lambda)$ of the luminescence emerging from the GaAs layer through the opposite surfaces, i.e., in the transmission and reflection geometries. It is known that the absorption coefficient in GaAs can vary by three to four orders of magnitude within the edge luminescence band and can reach levels of the order of $10^4$ at its short-wavelength edge [16]. As already mentioned, the radiation that is emitted in electron recombination in the bulk of the layer and exits through the two layer faces is weakened through self-absorption. Due to the nonuniform spatial distribution of electrons generated by stationary pumping near one of the layer faces, which is obtained by diffusion and recombination, the transmitted luminescence travels, on average, a longer path in the absorbing medium than the reflected one. The value of $I_u/I_{ref}$ is close to unity in the long-wavelength part of the spectrum (where the absorption coefficient $\alpha$ is small) and decreases with decreasing luminescence wavelength (i.e., with increasing $\alpha$). Thus, the $I_u/I_{ref}(\lambda)$ dependence carries information on the spatial distribution of nonequilibrium electrons in the crystal, which can be extracted by comparing the measured values of $I_u/I_{ref}(\lambda)$ with calculated ones. The sensitivity of this method is highest when the layer thickness is of the order of the electron diffusion length.

The $I_u/I_{ref}(\lambda)$ dependence can be expressed analytically as

$$I_u/I_{ref} = \frac{\int_{0}^{d} n(Z) e^{-\alpha(\lambda)(d-Z)} dZ}{\int_{0}^{d} n(Z) e^{-\alpha(\lambda)Z} dZ},$$

where $n$ is the electron concentration, $Z$ is the spatial coordinate along the crystal surface normal, and $d$ is the layer thickness.