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Spin-sensitive bleaching and spin relaxation in QWs

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Spin-sensitive saturation of absorption of infrared radiation has been investigated in *p*-type GaAs QWs. It is shown that the absorption saturation of circularly polarized radiation is mostly controlled by the spin relaxation time of the holes. The saturation behavior has been investigated for different QW widths and in dependence on the temperature with the result that the saturation intensity substantially decreases with narrowing of QWs. Spin relaxation times were experimentally obtained by making use of calculated (linear) absorption coefficients for inter-subband transitions.

1 Introduction The investigation of spin relaxation has attracted considerable attention in the past because of its great importance for the development of active spintronic devices [1]. Current investigations of the spin lifetime in semiconductor devices are based on optical spin orientation by inter-band excitation and further tracing the kinetics of polarized photoluminescence. These studies give important insights into the mechanisms of spin relaxation of photoexcited free carriers. Recently, the spin-sensitive bleaching of infrared absorption has been observed in *p*-type QWs yielding an access to spin relaxation processes under the condition of monopolar spin orientation [2]. In contrast to conventional methods of optical spin orientation using inter-band transitions [3] to create electron-hole pairs, in the infrared due to inter-subband transitions only one type of charge carriers is excited. Here we show that infrared spin orientation allows to study spin relaxation without electron–hole interaction and exciton formation.

2 Experiment The experiments have been carried out on *p*-type (113) MBE-grown GaAs QWs with various well widths L_W between 7 and 20 nm and on (001)-miscut QWs grown by MOCVD with a width of 20 nm. Samples with free carrier densities p_s of about 2×10^{11} cm^{-2} and a very high mobility μ of around 5×10^5 cm^2/(Vs) (at 4.2 K) were studied in the range of 4.2 K up to 120 K. As radiation source a high power far-infrared (FIR) molecular laser, optically pumped by a TEA-CO_2 laser, has been used delivering 100 ns pulses with intensities up to 1 MW/cm^2 at a wavelength range between 35 μm and 148 μm.

The intensity dependence of the absorption coefficient has been investigated showing that absorption saturates with higher intensities. It is observed that for circularly polarized radiation, compared to linearly polarized radiation, saturation takes place at a lower level of intensity. The basic physics of spin-sensitive bleaching of absorption is sketched in Fig. 1. Excitation with FIR radiation results in

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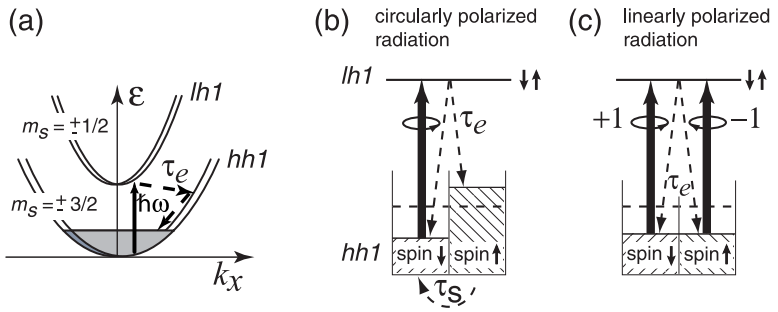

Fig. 1 Microscopic picture of spin-sensitive bleaching: a) direct *hh1–lh1* optical transitions. b) and c) process of bleaching for two polarizations. Dashed arrows indicate energy (τ_e) and spin (τ_s) relaxation.

direct transitions between heavy-hole *hh1* and light-hole *lh1* subbands. This process depopulates and populates selectively spin states in *hh1* and *lh1* subbands. The absorption is proportional to the difference of populations of the initial and final states. At high intensities the absorption decreases since the photoexcitation rate becomes comparable to the non-radiative relaxation rate to the initial state. For C_s-symmetry, relevant to our (113)-grown QWs, the selection rules for the absorption at $\boldsymbol{k}$ close to zero (but $\neq 0$) are $\Delta m = \pm 1$ so that only one type of spins is involved in the absorption of circularly polarized light. Thus the absorption bleaching of circularly polarized radiation is governed by energy relaxation of photoexcited carriers and spin relaxation in the initial subband (see Figs. 1a and b). These processes are characterized by energy and spin relaxation times τ_e and τ_s, respectively. We note, that during energy relaxation to the initial state in *hh1* the holes loose their photoinduced orientation due to rapid relaxation [4]. Thus, spin orientation occurs in the initial subband *hh1*, only. In contrast to circularly polarized light, absorption of linearly polarized light is not spin selective and the saturation is controlled by the energy relaxation only (see Fig. 1c). If τ_s is longer than τ_e, bleaching of absorption becomes spin-sensitive and the saturation intensity I_s of circularly polarized radiation drops below the value of linear polarization (see Fig. 2a).

The difference in absorption bleaching for circularly and linearly polarized radiation has been observed [2] employing the circular (CPGE) [5] and the linear (LPGE) photogalvanic effect [6]. The absorption coefficient is proportional to the photocurrent j_x normalized by the radiation intensity I. Figure 2a shows that j_x measured on p-type GaAs QWs depends on I as $j_x \propto I/(1 + I/I_s)$, where I_s is the saturation intensity. For different temperatures and QW widths our experiments show that saturation intensities I_s for circularly polarized radiation are generally smaller than for linearly polarized radiation (Fig. 3).

The non-linear behavior of the photogalvanic current has been analyzed in terms of excitation-relaxation kinetics taking into account both optical excitation and non-radiative relaxation processes. It

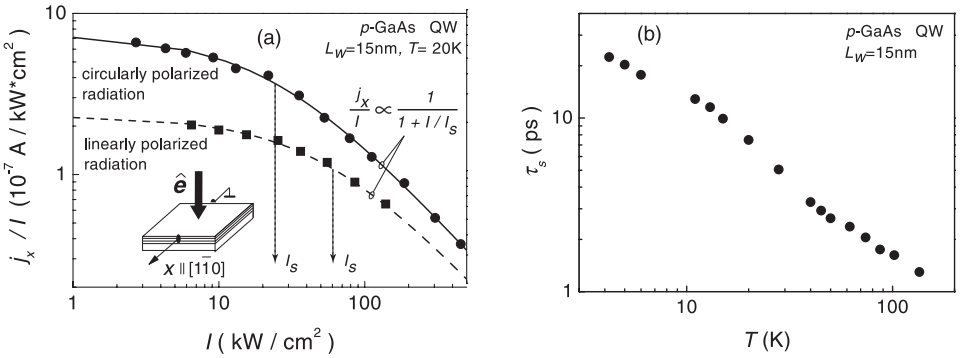

Fig. 2 a) CPGE and LPGE currents j_x normalized by intensity I as a function of I for circularly and linearly polarized radiation of $\lambda = 148$ μm, respectively [2]. b) Spin relaxation times obtained for p-type GaAs sample with a QW of $L_W = 15$ nm width, $p_s = 1.66 \times 10^{11}$ cm^{-2} and μ of about 5×10^5 cm^2/(Vs).

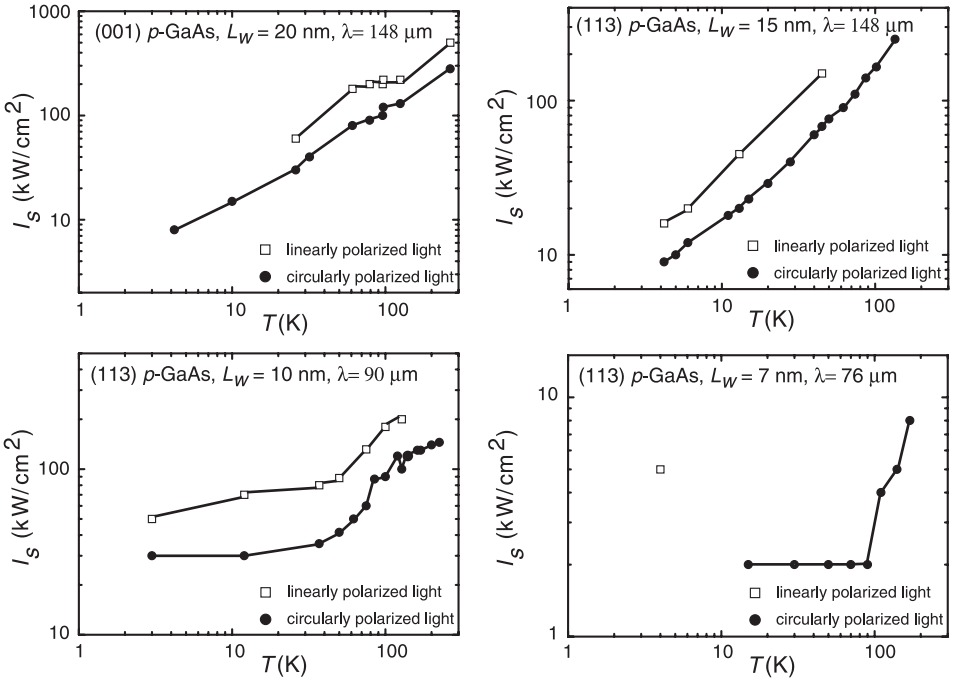

Fig. 3 Temperature dependence of the saturation intensities for various QW widths for linear (squares) and circular (circles) polarized light, respectively. The thickness of the QWs decreases from top left to bottom right. Note that the sample top left is miscut (001) grown.

can be shown [2] that the photocurrent j_{LPGE} induced by linearly polarized radiation is described by $j_{\mathrm{LPGE}}/I \propto (1 + I/I_{se})^{-1}$, where I_{se} is the saturation intensity controlled by energy relaxation of the hole gas. The photocurrent j_{CPGE} induced by circularly polarized radiation is proportional to $I/\left(1 + I\left({I_{se}}^{-1} + {I_{ss}}^{-1}\right)\right)$ where $I_{ss} = \hbar\omega p_s/(\alpha_0 L_W \tau_s)$ is the saturation intensity controlled by hole spin relaxation. Here α_0 is the absorption coefficient at low intensities and the spin relaxation time τ_s can be evaluated as

$$\tau_s = \frac{\hbar\omega p_s}{\alpha_0 L_W I_{ss}} \,. \tag{1}$$

In order to obtain τ_s the value of α_0 is needed which is determined theoretically. The calculations of the linear absorption coefficient α_0 for inter-subband transitions are based on the self-consistent multi-band envelope function approximation (EFA) [7], that takes into account the crystallographic orientation of the QW (here the (113) direction) and the doping profile. Calculations are performed here within the Luttinger model of the heavy and light hole states to obtain the hole subband dispersion $\epsilon_i(\boldsymbol{k})$ and eigenstates $|i, \boldsymbol{k}\rangle$ of the hole subband i and in-plane wave-vector $\boldsymbol{k}$. For direct (electric dipole) transitions between subbands i and j the contribution to the absorption coefficient $\alpha_{i\to j}(\omega)$ as a function of the excitation energy $\hbar\omega$ is then given by [8]

$$\alpha_{i\to j}(\omega) = \frac{e^2}{4\pi\epsilon_0 \omega c n L_W} \int d^2k \, |\langle j, \boldsymbol{k}| \, \boldsymbol{e} \cdot \hat{\boldsymbol{v}}(\boldsymbol{k}) \, |i, \boldsymbol{k}\rangle|^2 \left[f_j(\boldsymbol{k}) - f_i(\boldsymbol{k})\right] \frac{\mathrm{e}^{-\left(\epsilon_j(\boldsymbol{k}) - \epsilon_i(\boldsymbol{k}) - \hbar\omega\right)^2/\Gamma^2}}{\sqrt{\pi}\,\Gamma} \,, \tag{2}$$

where $\boldsymbol{e}$ is the light polarization vector, n is the refractive index, ϵ_0 is the free-space permittivity, $f_i(\boldsymbol{k})$ is the Fermi distribution function in the subband i and Γ is a broadening parameter to account for the level broadening due to scattering. Within EFA, the velocity $\hat{\boldsymbol{v}}(\boldsymbol{k})$ is a matrix operator expressed as the gradient in $\boldsymbol{k}$-space of the Luttinger Hamiltonian. Its matrix elements are calculated from the EFA wave functions.

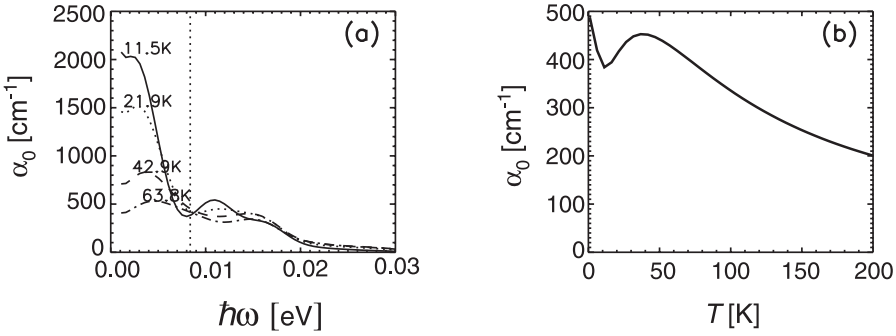

Fig. 4 Absorption coefficient as a) a function of photon energy $\hbar\omega$ for various temperatures and b) a function of T for $\hbar\omega = 8.4$ meV (vertical dotted line in a)), calculated for a (113)-grown 15 nm GaAs–AlGaAs QW with carrier density 2×10^{11} cm^{-2}. The broadening Γ was set to 2.47 meV.

Following this scheme we calculate the absorption coefficient $\alpha_0(\omega) = \sum_{ij} \alpha_{i-j}(\omega)$. The absorption spectrum for the system with $L_W = 15$ nm is shown in Fig. 4a. At low temperatures two pronounced peaks evolve, which correspond to the transitions from the lowest (spin split) hole subband to the second and third subband, respectively. Figure 4b shows the temperature dependence (due to the Fermi distribution function) of α_0 at the excitation energy for the sample with $L_W = 15$ nm. Using experimentally obtained I_{ss} together with the values of α_0 calculated according to the above mentioned theoretical scheme, spin relaxation times can be obtained [2]. The results for QWs of $L_W = 15$ nm are shown in Fig. 2. Compared to the values given in [2], where α_0 was derived from [8], we obtain here smaller τ_s at high temperatures due to a more realistic theoretical model for the calculation of α_0. We note that in the definition of I_{ss} it was assumed that the spin selection rules are fully satisfied at the transition energy. This is the case for optical transitions occurring close to $\boldsymbol{k} = 0$ in (001)-grown systems [4]. However, in (113)-grown systems, heavy-hole and light-hole subbands show a strong mixture, which exists even at $\boldsymbol{k} = 0$. This reduces the strength of the selection rules [9] and therefore the efficiency of spin orientation. The mixing can be taken into account by means of a multiplicative factor in I_{ss}, which increases the saturation intensity at constant spin relaxation time. Figure 3 presents the results for I_{ss} for QWs of various widths at different temperatures. A significant reduction of I_{ss} with decreasing L_W is to be pointed out. This observation indicates longer hole spin relaxation times for narrower QWs in accordance with calculations by Ferreira and Bastard [4]. A verification of this tendency requires the extraction of spin relaxation times for all investigated QW widths from experimentally obtained I_{ss} shown in Fig. 3, as it was done for $L_W = 15$ nm (see Fig. 2b).

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