Extended Abstracts of the 2004 International Conference on Solid State Devices and Materials, Tokyo, 2004, pp. 896-897

G-9-2

Long-range spin transport by acoustic fields in GaAs quantum wells

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1. Introduction

The manipulation and transport of spins are critical steps towards the realization of novel, functional devices for information processing, quantum computing, and quantum cryptography. Recently, we have demonstrated that the piezoelectric field induced by a surface acoustic wave (SAW) can be applied to increase the lifetime of photogenerated spins and transport them in semiconductor quantum wells (QWs).[1,2] The mobile character of the SAW provides new degrees of freedom for the manipulation and transfer of quantum information between microscopic systems. A further advantage of using acoustic fields is the possibility of manipulating carriers and spins using purely optical techniques.

One of the limitations of the SAW-induced spin transport is related to the slow acoustic propagation velocities, which require very long spin lifetimes for long (i.e., several µm) transport lengths. In fact, the spin transport lengths in (100) GaAs QWs measured up to now are less than 10 µm.[2] In this work, we demonstrate that spin transport lengths approaching 20 µm can be obtained in (110) GaAs/AlGaAs QWs. The longer spin lifetimes and transport lengths in these QWs under SAW fields are attributed to the quenching of the excitonic [3] and D'yakonov-Perel (DP) spin relaxation mechanisms in (110) QWs.[4,5]

2. Experimental details

The spin transport experiments were carried out on a 20 nm-wide GaAs QWs with (AlGa)As barriers grown by molecular beam epitaxy on a (110) GaAs substrate. The growth conditions were optimized in order to produce QWs with narrow (full width at half maximum <1.3 meV) photoluminescence (PL) lines for the excitonic transitions.

Figure 1(a) shows a schematic diagram of the setup for optical detection of spin transport by SAW fields. SAWs propagating along the *x*=[001] direction of the (110) surface were generated by focusing interdigital transducers (IDTs) designed for operation at an acoustic wavelength and frequency of λ_{SAW}=5.6 µm and f_{SAW}=509 MHz, respectively. The focusing IDTs generate a narrow (width of a few λ_{SAW}) SAW beam, which acts as an efficient channel for acoustic transport.[6] The carriers were photogenerated at a position G on the SAW path by a focused laser spot (diameter of approx. 2 *µm*) from a Ti-Sapphire laser using a microscope objective. The excitation wavelength of 760 nm is approx. 100 *meV* above the QW electron-heavy hole (*e-hh*) excitonic transition. The incident beam was right circularly polarized using a quarter wave plate in order to generate carriers with spin polarization along the growth direction. The PL along the transport path (*x*-direction) was collected using the same objective and analyzed with respect to its polarization. We will denote that intensity of the PL components with right and left circular polarizations as I_R and I_L, respectively. These components yields are proportional to the density of carriers with up- and down spins, respectively. They were used to determine the degree of spin polarization *r*, which is defined as $r_S=(I_R - I_L)/ (I_R + I_L)$.

Maps of the spin density were obtained by imaging the PL along the transport channel using a CCD camera. The *e-hh* excitonic PL of the QW was spectrally selected using a monochromator or band-pass filters. In order to increase the PL intensity away from the generation point, a semi-transparent metal layer [M in Fig. 1(a)] was deposited on the transport path in order to short-circuit the piezoelectric potential and induce carrier recombination. All experiments were performed at temperatures from 15 to 30 K.

3. Results and discussions

The thick and thin lines in Fig. 1b show profiles of the integrated PL intensity with right (I_R) and left (I_L) circular polarization, respectively, as a function of the distance *x* from the generation point G. In this particular measurement, G was located approx. 16 µm away from the edge of the metal stripe M and the SAW was generated by applying a nominal radio-frequency (rf) power of 20 dBm to the IDT. In the absence of a SAW, the PL intensity decreases exponentially away from G and practically vanishes for |*x*|>2 µm.

The SAW leads to a strong reduction of the PL as the photogenerated carriers are transported away with the SAW propagation velocity of v_{SAW}=2850 m/s. During the transport, the electrons and holes are stored in the regions close to the maxima and minima of the piezoelectric potential, respectively. The spatial carrier separation prevents their recombination and allows for transport over several tens of µm. The partial screening of the piezoelectric potential under the metal layer leads to an increased PL at position M. Note, however, that the screening of the SAW piezoelectric field for *x*>16 µm [Fig. 1(b)] is not complete and the carriers are further transported below the metal.

In addition to the strong PL at M, we also observe considerable recombination between G and M. The latter is

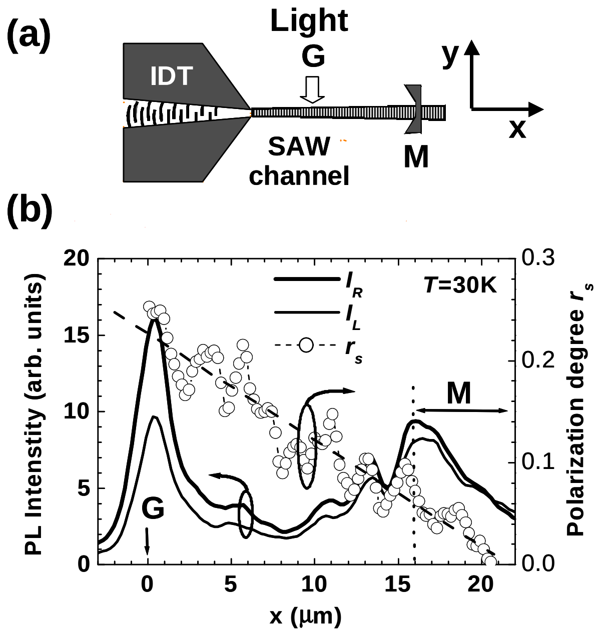

Fig. 1 (a) Experimental setup for optical detection of spin transport by SAW fields. The SAWs are generated by a focusing interdigital transducer (IDT). Spin-polarized carriers are photogenerated by a circularly polarized laser spot at position G and acoustically transported along the SAW path to the metal stripe M, where they are forced to recombine. (b) Profiles of the integrated PL intensity with right (I_R) and left (I_L) circular polarization. The open circles show the degree of circular polarization r_s.

attributed to defects along the SAW beam, which capture the carriers and induce their recombination. Although the nature of these radiative traps in (110) QWs has so far not been studied in details, we conjecture that they are due to potential fluctuations induced by interface roughness and variations in the QW thickness. We also note that the PL profiles show oscillations with the acoustic periodicity, which are attributed to acoustic interference effects induced by the focusing IDTs.

The intensity of the I_R PL component remains higher than that of the I_L one for distance up to 20 µm away from G. The circles in Fig. 1(b) show profiles for the degree of circular polarization r_S determined from the I_R and I_L curves. At the generation point, r_S increases from 15% to over 20% when the SAW is switched on. This behavior has been reported in previous investigations of (100) GaAs QWs and attributed to the quenching of the electron spin relaxation via exchange interaction.[1,2] The same mechanism seems to apply for the (110) QWs.

The spin polarization r_S decays away from G and amounts to only approx. 5% at the edge of the metal layer at x=16 µm. The mechanism for the unusual linear decay is not known at present. We note the PL distribution is inhomogeneous along the transport path reflecting an inhomogeneous distribution of radiative trapping centers. We, nevertheless, define the spin transport length l_S as the distance where the polarization degree decays to 1/3 of the value at the generation point. By performing measurements for different separation between the G and M, we consistently obtained l_S=13 µm. From this length we calculate a spin lifetime $\tau_S=l_S/v_{SAW}$=4.6 ns.

The spin transport lengths in (110) QWs are considerably longer than those of the order of 3-5 µm measured for SAW-induced spin transport in (100) GaAs QWs.[1,2] The long transport lengths are attributed to two effects that increase the electron spin lifetime in (110) QWs (we assume that the hole spin relaxes much faster than the electron one). The first is the previously mentioned reduction of the exchange interaction due to the spatial separation between electrons and holes in the type II potential profile induced by the SAW.[1,3]

The second mechanism is associated with the fact that spin relaxation through the DP mechanism [4] becomes ineffective for spins oriented along the growth axis of (110) QWs.[5] The effective magnetic field responsible of the DP relaxation is also oriented along [110] in these QWs and can, therefore, not change the spin component along this direction. These results also unambiguously demonstrate that the DP effect is the dominating spin relaxation mechanism during the acoustically induced spin transport in (100) QWs.

3. Conclusions

We have demonstrated long spin lifetimes under SAW fields as well as acoustically induced transport lengths exceeding 10 µm in a (110) QW. These effects are attributed to the reduction of spin scattering through the exchange and DP mechanisms. The long lifetimes and transport lengths clearly demonstrate the feasibility of using SAW fields for the spin manipulation in spintronic devices.

Acknowledgements

F. I. thanks the Alexander von Humboldt Foundation for financial support.

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