J Supercond Nov Magn (2007) 20: 461–465
DOI 10.1007/s10948-007-0237-4

Spin Dynamics in Narrow-Gap Semiconductor Epitaxial Layers

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Received: 18 June 2007 / Accepted: 22 June 2007 / Published online: 11 August 2007

Abstract We report on investigation of the spin dynamics in InAs and InSb films grown on GaAs at a temperature range from 77 K to 290 K. For both materials, the large lattice mismatch with the GaAs substrate results in the formation of an interface accumulation layer with a large defect concentration, which strongly affects the spin relaxation in these areas. Moreover, the native surface defect in the InAs films resulted in an additional charge accumulation layer with high conductivity, but very short spin lifetime. In contrast, in InSb layers, the surface states introduce a depletion region. We have correlated the spin relaxation with a multilayer analysis of the transport properties, and find that in a 1 μm thick InAs film, approximately 70% of the total current flows through the interface and surface accumulation layers, which have sub-picosecond lifetimes, whereas in InSb films of the same thickness, the semiconducting layer carries more than 90% of the total current, and the spin lifetime in the accumulation layer is only slightly less than that of the central semiconducting layer. We suggest that InSb could be a more attractive candidate for spintronic applications than InAs.

Keywords Spin dynamics · Transport · InAs · InSb · Spintronics

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1 Introduction

The electron spin dynamics has been extensively studied due to the potential for the development of a remarkable new generation of electronic devices. Spintronic devices, which exploit the spin of the electrons rather than charge, have been demonstrated to be more efficient in some areas than conventional electronics. The prototype device that is already widely in use in industry, as a read head for magnetic disks and a memory-storage cell, is the giant-magnetoresistive structure which consists of ferromagnetic and nonmagnetic metal layers. In spite of the obvious success of the metal-based devices, introducing semiconductor materials into spintronics is of great importance, because semiconductor based devices could provide amplification, serve as multi-functional devices, and be more easily integrated with traditional semiconductor technology.

It is desirable for spintronics to be able to control spin dynamics with an external electric field. When the D'yakonov–Perel (DP) spin relaxation mechanism [1] is dominant, it is possible to control spin lifetime with the applied electric field by modulating the strength of the spin-orbit coupling through the Rashba effect. It was shown that the DP process dominates over the other spin relaxation processes such as Elliot–Yaffet (EY) [2, 3], and Bir–Aronov–Pikus (BAP) [4] in high mobility materials down to very low temperatures [5]. The BAP mechanism is only efficient in p-type semiconductors. The efficiency of spin relaxation mechanisms strongly depends on the carrier concentration and mobility. Although most investigations have been focused on GaAs-based semiconductor materials, we believe that narrow-gap semiconductors (NGS) are of particular interest because of their strong spin-orbit coupling, small electron effective mass and high electron mobility. Moreover, the presence of surface charge layers InAs and InSb, could be used to design a contact with metallic materials without a significant resistance mismatch and consequent need for Schottky barrier. In this paper, we compare the spin dynamics properties of InAs and InSb films grown on semiinsulating GaAs substrates by molecular beam epitaxy (MBE).

The lattice mismatch with the GaAs substrate, which is 14.6% for InSb and 7% for InAs, results in the formation of a large defect concentration and creation of an interface accumulation layer with high carrier concentration and low mobility. The electron mobility in this layer is found to be several orders of magnitude smaller than that in bulk materials. In comparison with other common semiconductors, the InAs uniquely has electron accumulation in the near-surface region [6]. In contrast, a low-barrier depletion region is formed on the surface of the InSb films. The InAs surface accumulation layer is very useful for fabricating nanometer-scale conducting semiconductor structures, nanowires [7], and nanoelectromechanical systems [8]. However, its sub-picosecond spin lifetime reported in this paper could rule out the usefulness of InAs for spintronic applications. On the other hand, InSb films have all advantages of narrow-gap materials, but without the complication of the surface accumulation layer.

In the following for simplicity, we shall assume that both InAs and InSb films grown on GaAs consist of three regions: (i) the interface layer, which has high carrier concentration and low mobility for both materials; (ii) the bulk-like layer with low carrier density and high mobility; and (iii) the surface accumulation layer for InAs with high carrier concentration and low mobility and the surface depletion layer for InSb.

2 Experiment

Hall measurements were performed on 5 mm diameter clover-leaf Van der Pauw patterns in order to measure the mobility and carrier concentration in the temperature range from 77 to 300 K. A number of InAs and InSb films of different thicknesses were investigated. In order to obtain a depth profile of the electron mobility and carrier concentration, we assumed that the properties of the thinner film and the region of the same thickness of the thicker film of any pair of films are the same. Thus, the properties of the remaining top region of the thicker film can be found differentially using the standard multi-layer Hall formula [9], derived from the basic two-layer method of Petritz [10].

The InAs and InSb films were grown on semiinsulating GaAs (001) substrate using a VG Semicon V80 molecular-beam epitaxy (MBE) system. In order to improve the interface property of InSb films, an advanced two-step growth recipe has been developed at Imperial College. First, a 20 nm InSb low temperature (LT) buffer was grown on GaAs (100) substrate, and then the sample was annealed at a high temperature (HT). An additional investigation was performed to optimize the temperature of the HT growth step, which was found to be 380 °C. A remarkable improvement of the transport properties were reported for these samples [11].

The spin relaxation times were investigated by means of a circularly polarized pump-probe experiment. The change in the transmission induced by a circularly polarized pump beam was measured by a probe beam, which had the same (SCP) or opposite circular polarization (OCP), as a function of the time delay between pump and probe beams. The spin lifetime could be retrieved from the time evolution of the spin polarization which is proportional to the detected optical polarization $(\mathrm{SCP}-\mathrm{OCP})/(\mathrm{SCP}+\mathrm{OCP})$. A ZnSe photoelastic modulator (PEM) was used to modulate the polarization of the pump beam. The laser radiation with pulses shorter that 100 fs was provided by a difference frequency generator (DFG) at a repetition rate of 250 kHz. The DFG was pumped by an optical parametric amplifier (OPA), itself pumped by an amplified Ti:sapphire oscillator. The wave length of DFG output could be tuned from 3 to 13 μm, which allowed us to maintain the photon energy just above the band gap for both materials over the whole temperature range.

In order to identify the contribution of the different regions to electron transport and spin dynamics, we studied three samples of each material with different thickness of the epitaxial layers: 0.15 μm, 0.27 μm, 1 μm InAs films; and 0.1 μm, 0.3 μm, 1 μm InSb films. The room temperature decays of spin population of all films under investigation are shown in Fig. 1.

3 Results and Discussion

The knowledge of the depth profile of the mobility and carrier concentration is crucial for understanding the spin dynamics in semiconductor structures, because the spin relaxation mechanisms strongly depend on these parameters. The DP mechanism is inversely proportional to the electron mobility, whereas the EY mechanism is linearly proportional to it. The crossover between two mechanisms occurs at [9]

$$\mu^{(\mathrm{co})} = \frac{\alpha}{\beta}\frac{e\hbar}{m}\sqrt{\frac{A}{QE_G E_k}},$$

where α and β are dimensionless parameters which depend on the band structure of the semiconductor. A and Q are also dimensionless parameters which are determined by the scattering mechanism: $A = 6$ and $Q = 32/21$ for ionized impurity scattering, and $A = 2$ and $Q = 96/35$ for lattice scattering [1, 5]. E_G is the band gap energy, and E_k is the electron kinetic energy which is equal to $k_B T$ for nondegenerate statistics and to the Fermi energy E_F in the limit of degenerate

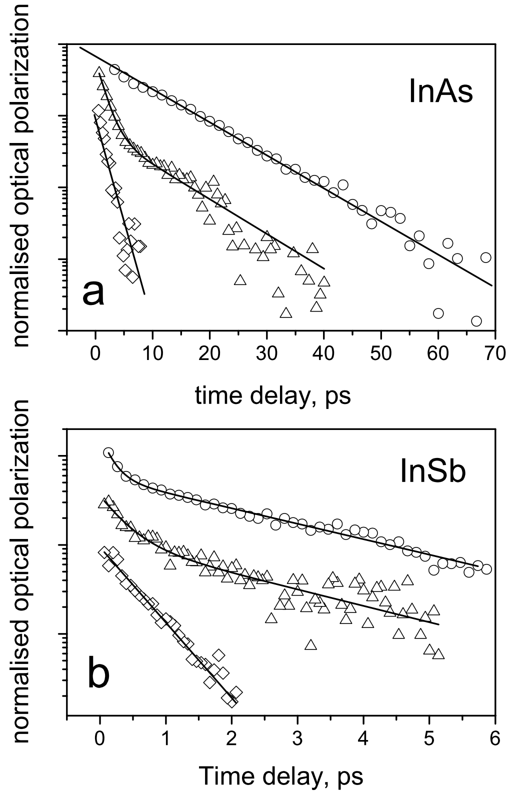

Fig. 1 Time evolution of the spin population measured at room temperature for undoped **a** InAs films of thicknesses 0.15 µm (*diamonds*), 0.27 µm (*triangles*), 1 µm (*circles*); and **b** InSb films of thicknesses 0.1 µm (*diamonds*), 0.3 µm (*triangles*), 1 µm (*circles*)

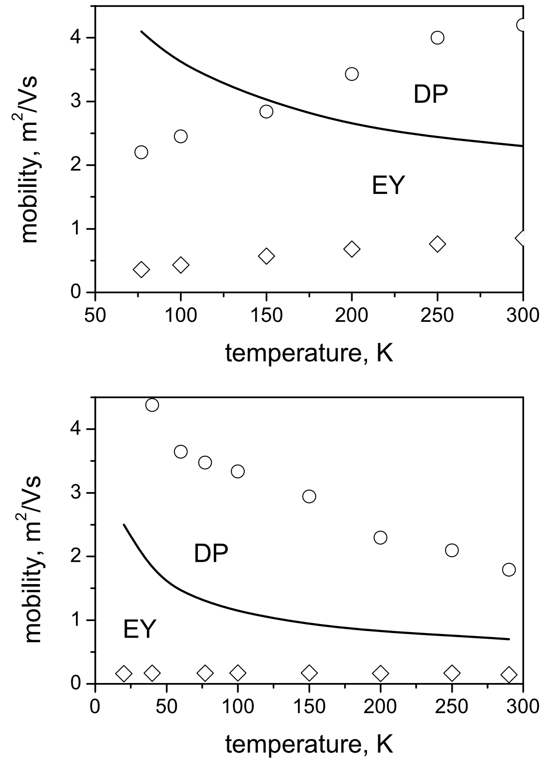

Fig. 2 Temperature dependence of the derived mobility of the interface layers (*diamonds*), and bulk-like layers (*circles*) deduced by multi-channel differential analysis of the set of **a** InAs and **b** InSb films. The parameters of each layer are presented in Table 1. The crossover mobility between the DP and EY processes is shown by the *solid lines*

statistics. In [5], it was shown that in high mobility semiconductors the EY mechanism dominates only at very low temperatures even in NGS, where the efficiency of the EY process is larger. The situation is different in low mobility materials. It was already demonstrated that the crossover between the EY and DP process in doped InSb quantum wells could occur even at room temperature [12].

A detailed investigation of the transport properties has been presented elsewhere for InAs [9] and InSb films [11, 13–15]. It was shown that for both materials, the interface layers have high carrier concentration and low mobility. The thickness of the interface layer is found to be about 100 nm in both materials. The bulk-like regions have low carrier concentration and high mobility. The properties of the surface layers are different. In InAs, an accumulation surface layer of 50 nm thickness is formed. It carries most of the current, has high carrier concentration and comparably low mobility [9], whereas for InSb, the influence of the depletion surface layer on the transport property could be ignored [15]. The temperature dependences of the electron mobility in both InAs and InSb films are shown in Fig. 2 by symbols. The crossover between the EY and DP processes is also shown by solid lines for the case of lattice scattering and nondegenerate statistics. The DP mechanism dominates in both materials at room temperature in the bulk-like region. In the interface layers and InAs surface layer, the EY mechanism dominates for the whole temperature range. (The magnitude of $\mu^{(co)}$ for the ionized impurity scattering case is more than two times larger than the mobility required for lattice scattering case).

Let us now consider the spin relaxation (see Fig. 1). The decay of spin population of the thickest 1 µm films of both InAs and InSb can be described by a single exponential decay. The spin lifetimes extracted from these decays are very similar to the spin lifetime measured in bulk InAs [16] and InSb [15]. This suggests that the measured spin lifetime in these samples is due to spin relaxation in bulk-like regions. The films of intermediate thicknesses exhibit two exponential decays. We attribute the longer lifetime component to the bulk-like region, because of its similar magnitude to the 1 µm samples. The spin lifetimes measured for the thinnest films have similar magnitude as the short components of the spin lifetime of the intermediate films, which suggests that they have the same origin. For InSb, it is obviously the interface layer. For 0.15 µm and 0.27 µm InAs films, it was found that in the interface layers the mobilities and carrier concentrations have the same values, whereas because of the diffusion of the interface defect to the surface, the surface

Table 1 The depth-dependent properties of the InSb and InAs 1 μm films deduced from the differential model. d is the width of the layer, x is relative amount of the total current flowing through the layer, and τ_s is the spin lifetime. For InSb film, the property of the LT buffer layer is also shown

Layers	InSb				InAs		
	LT baffer	Interface	Bulk-like	Surface	Interface	Bulk-like	Surface
d, nm	20	100	850	100	100	850	50
μ, m^2/V s	0.035	0.85	1.8	–	1.5	17	5.0
n, 10^{-16} cm^{-3}	49	4.9	3.6	–	25	0.7	90
τ_s, ps	<0.017	0.56	2.5	–	1.4	11.7	<0.03
Spin relaxation process	EY	EY	DP	–	EY	DP	EY
x, %	≈0.5	≈7	≈92.5	–	≈10	≈28	≈62

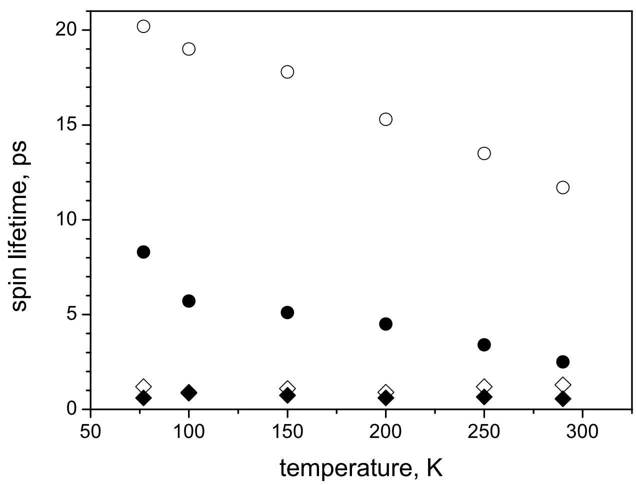

Fig. 3 The temperature dependence of the spin lifetime in the bulk-like (*circles*) and interface (*diamonds*) layers of InAs (*open symbols*) and InSb (*solid symbols*) films

mobility in the 0.15 μm film is more than 3 times smaller than that in the 0.27 μm film. Moreover, the surface electron Fermi energy is estimated to be about 300 meV for InAs films, which leads to a large Moss–Burstein shift in the absorption edge, and the impossibility of optical creation of a spin population. We suggest that the short component of the spin lifetime in InAs film also originates from the interface layer. The temperature dependence of the spin lifetime in the bulk-like and interface layers for both materials are shown in Fig. 3.

All our room temperature results are gathered in Table 1. The current carried by each layer is proportional to $\mu n d$ (see Table 1), so that the fraction of the current flowing through each layer can be estimated. It was found that more than 60% of the current flows through the surface layer of the InAs films. These films have short spin lifetime, which is controlled by the degenerate EY process. Although in InSb bulk-like region the spin lifetime is 4 times less than in InAs bulk-like regions, the fraction of current flowing through such regions is considerably higher (92.5%). We infer that InSb could be a more useful for spintronic application than InAs.

4 Conclusion

We have investigated the spin dynamics for undoped InAs and InSb films of different thicknesses between 0.1 and 1 μm. The spin relaxation has several components which originate from different layers of the films. The spin lifetime in the interface layer is nearly one order of magnitude less than in the bulk-like region, but this layer carries not more than 10% of the total current. Because of the high carrier concentration, and consequently, large Fermi energy in the surface accumulation layer of InAs films, the spin lifetime in the layers is estimated to be less than 30 fs, while 60% of the whole current flows thorough the surface layer of the 1 μm InAs film. The EY spin relaxation mechanism dominates in the surface and interface regions of the both InAs and InSb films. In the 1 μm InSb films, the bulk-like region carries more than 92% of the whole current. The spin lifetime is in the picosecond range and governed by the DP process, which makes it a more attractive candidate for spintronic application. In order to use InAs material in designing lateral spintronic devices, the influence of the surface has to be reduced.

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