1. Introduction

High spin polarization devices are necessary for the successful development of semiconductor spintronics [1–3]. It has been suggested that by using the spin of the electron to control devices rather than the current, improvements in speed and energy efficiency of electronic devices can be obtained as well as allowing for quantum qubits to be designed [4, 5]. Due to the difficulty of creating highly spin-polarized semiconductor materials at ambient temperature [6] one of the most promising routes is to combine highly polarized ferromagnetic metals as spin-injectors with non-magnetic semiconducting channels. Measuring the polarization across the interface between the polarized injector material and the semiconductor structure plays an important role in materials selection. The interface plays an essential role as evidenced by the fact that half-metallic materials (with bulk polarization approaching 100%) do not translate into equivalent high spin polarizations when combined with GaAs devices [7, 8]. Fe spin-injecting contacts, with a bulk polarization of ~40%, have provided the highest spin-injection polarizations of all the simple metals. Fe is closely lattice matched to GaAs and the interface between these materials has been studied in depth [9–13].

In the work presented here, the spin-polarization as a function of temperature using an Fe contact on an InGaAs quantum well LED device is investigated where the transfer between the III–V and metals growth chamber was carried out in situ.
The electroluminescence from the In_{0.2}Ga_{0.8}As quantum well is presented. Optical measurements show the temperature dependence of the spin lifetime of recombining electrons, which fits a D’yakonov–Perel’ model. In section 2 we discuss the device growth and fabrication. In section 3, results from the two optical techniques are presented. Section 4 is a discussion of the results and the main experimental findings with a final summary in section 5.

2. Device fabrication

The LEDs are molecular beam epitaxy (MBE) grown p-i-n junctions with a quantum well in the centre of the intrinsic region. The semiconductor structure consists of 15 nm n-Al_{0.1}Ga_{0.9}As (5 × 10^{18} cm^{-3})/15 nm n-Al_{0.1}Ga_{0.9}As (1 × 10^{18} cm^{-3})/100 nm n-GaAs (1 × 10^{18} cm^{-3})/100 nm GaAs/10 nm In_{0.2}Ga_{0.8}As/100 nm GaAs/500 nm p-GaAs (5 × 10^{18} cm^{-3}) grown on a p-type (1 × 10^{18} cm^{-3}) GaAs substrate. This wafer has been used for previous studies [14, 18] and has a heavily doped n-type layer at the surface that is designed to produce a narrow Schottky barrier with the Fe contact. The Schottky barrier provides a tunnelling contact that is required to maintain a high spin-polarization between materials that have different resistivities [19, 20]. The sample was then transferred in situ under UHV to a metals growth chamber with a base pressure of 2 × 10^{-10} mbar. A 5 nm thick epitaxial Fe layer was deposited at ambient substrate temperature at a rate of 0.03 nm s^{-1}. Finally, the wafer was capped with 5 nm of Au to protect the Fe layer from oxidation upon removal from the vacuum chamber, prior to device processing. The LED devices were wet etched into 200 μm by 100 μm mesa using standard optical lithography. The p-type contact was formed by low-temperature 180 °C annealed In–Zn with evaporated Ti–Au top bonding contacts. The magnetic Fe contact was characterized using magneto-optical Kerr effect (MOKE) magnetometry, to confirm the four-fold magnetic anisotropy expected from epitaxial growth of Fe on GaAs [18]. The in-plane cubic easy axis switching fields were ~1.5–1.7 mT.

3. Optical measurements

The electroluminescence from the In_{0.2}Ga_{0.8}As quantum well in the device, measured at 4 K with a constant current of 0.4 mA, is shown in figures 1(a) and (b). The data is shown for +0.83 T, +0.03 T and –0.83 T applied magnetic field in the oblique Hanle configuration. For the data at applied fields the two polarization states are shown, with figure 1(b) being a close-up of the peaks shown in figure 1(a). The designed quantum well e1 hh1 emission energy is around 1.32 eV, significantly lower than the peak seen here at around 1.40 eV, with a shoulder at 1.41 eV. However, the energy is too low to be associated with recombination in the bulk of the device [21]. Thickness variations across the semiconductor wafer that occur during MBE growth of the heterostructure layers can alter the dominance of where the emission originates from in these devices [14]. We also observe variation in the position of the quantum well peak across the wafer which may be due to indium segregation which can occur in such pseudomorphically strained layers [22] depending on the growth conditions. It is also noticeable that the emission varies between the data sets. This is likely to be due to the drift in the device temperature due to the relatively large current density required for emission.

The LEDs were measured in the Faraday geometry [10], where a perpendicular magnetic field, large enough to saturate the hard axis magnetization, is applied out-of-plane. A second system was used to measure the devices in the oblique Hanle geometry, where a small magnetic field is applied at an angle (ϕ) to the normal to the sample [7, 14, 16] to saturate the Larmor precession, Ωτ ≫ 1, where Ω is the Larmor frequency and τ is the spin lifetime. In both cases the optical polarization efficiency of the measured light is defined as $P = \frac{I_+ - I_-}{I_+ + I_-}$, where $I_+$ ($I_-$) is the intensity of left (right)-hand polarized light.
peak at 1.395 eV and a negative peak at 1.405 eV. In the oblique Hanle geometry a magnetic field is applied at a fixed angle (\(\phi\)) to the normal of the sample (in this case 60°). As the field is increased the spins tend to align with the magnetic field. The shape of the curve depends on the spin-polarization, spin lifetime and recombination lifetime of the spins in the quantum well. The circular polarization of the light directly gives the spin-polarization of the electrons (\(S_e\)) which is given by:

\[
S_e = \frac{\tau_s}{\tau_s + \tau_R} \frac{1}{1 + (\Omega T)^2} \cos \phi \sin \phi
\]

where \(S_0\) is the initial spin-injection polarization, \(\tau_s\) is the spin scattering time, \(\tau_R\) is the electron radiative lifetime, the spin lifetime (\(T_s\)) is defined as:

\[
T_s^{-1} = \frac{1}{\tau_s^{-1} + \tau_R^{-1}}
\]

and \(\Omega\) is the Larmor precession frequency given by

\[
\Omega = g^* \frac{\mu_B}{\hbar} B,
\]

with \(g^*\) the electron Landé g-factor, \(\mu_B\) the Bohr magneton, \(\hbar\) Planck’s constant and \(B\) the applied magnetic field. We then fit \(S_e\) from the optical polarization as a function of applied magnetic field. From the Hanle fit the spin lifetime in the device is extracted in addition to the spin-injection polarization in the quantum well. We use a \(g^*\)-factor in these fits of ~0.8 taken from measurements on similar quantum wells [23]. Due to the quantum mechanical selection rules recombination of electrons with heavy holes and light holes gives opposite optical polarizations [17]. This may explain the negative polarization peak seen at higher energy. However, it would be expected that the light-hole peak was separated by around 50 meV from the heavy-hole peak [24], rather than the 10 meV seen here.

In figure 4 the quantity \(S_0 T/\tau_R\) is plotted on the left-hand axis versus temperature, where \(S_0 T/\tau_R\) is the optical polarization of the electrons in the quantum well. This is the quantity directly measured in the Faraday geometry and the quantity extracted from the Hanle equation from the geometry of the measurement. This is the polarization after degradation from transit through the device and more importantly, the time spent in the quantum well. Transit through the device will account for a few ps whilst the decay time in the well will be \(>100 \text{ps}\) [25]. The measured spin lifetime, \(T_s\), will have contributions from both the transit through the device and the time in the quantum well. At low temperature there is a good agreement between the two experimental procedures.

This method can also be used to extract the spin-polarization across the interface if \(T_s\) the spin lifetime, which comes from the Hanle fit, and \(\tau_R\), the radiative lifetime, which needs to be determined separately, are known. Using time-resolved photoluminescence on an equivalent undoped sample the electron lifetime was determined as 400 ps at 4 K. This allows the interfacial injection polarization, \(S_0\), to be estimated as 50 ± 20% at 4 K, which is in line with other measurements [11, 12, 26] and the expected spin-polarization of Fe [27].

Oblique Hanle effect measurements were made at temperatures from 4 K to 300 K and Hanle curves were fitted to give the spin lifetime and optical polarization in the well (\(S_0 T/\tau_R\))
T ~4.5% to ~1% at ambient temperature. Since we see constant decrease with temperature from the low temperature peak of region [29]. The polarization in the quantum well is seen to scattering as would be expected from the n-type doped transit. The momentum scattering is dominated by charged impurity

Figure 3. (a) Optical polarization measured as a function of applied magnetic field in the Hanle geometry at 4.2 K with 0.4 mA current. (b) The Hanle curve experimental data points and fits at 1.397 eV, for the heavy hole emission peak.

over the temperature range as shown in figure 4. The 30 to 40 ps spin lifetime has very little dependence on temperature. This flat temperature dependence is similar to that previously seen in other quantum well systems and indicates the dominance of the D’yakonov–Perel’ mechanism over the whole temperature range [17, 28]. It also shows that the spin lifetime is dominated by the quantum well rather than transit through the device, as bulk spin relaxation under the D’yakonov–Perel’ mechanism gives a temperature (T) dependence of $T^{-3/2}$ if the momentum scattering is dominated by charged impurity scattering as would be expected from the n-type doped transit region [29]. The polarization in the quantum well is seen to decrease with temperature from the low temperature peak of ~4.5% to ~1% at ambient temperature. Since we see constant $T_s$ in the device across the temperature range, this decrease in polarization is likely to be due to an increase in the radiative lifetime of the electrons at higher temperatures [30].

4. Discussion

The similar polarizations seen in the Faraday and oblique Hanle geometries show that there is no dependence of the relative orientation of the magnetization with the interface that would manifest as a tunnelling anisotropic magnetoresistance (TAMR) signal [31]. Whilst large TAMR effects have been seen in specially designed samples, for Fe/GaAs interfaces the numbers are quite small, <1% of the total signal [32], which is well within the errors of this experiment. These effects may become more pronounced if Heusler alloys [33], or synthetic multilayers, are used to create spin-injecting elements in spintronic devices. The interfacial Schottky barrier in GaAs, due to the dominance of conduction at the Γ-point in k-space is unlikely to have a large TAMR effect.

Whilst the results from both experiments are consistent, it is notable that the polarizations are small. In similar systems optical polarizations of 30% have been measured [11, 12, 26]. The lower value seen here is consistent with the relatively small spin lifetimes that we extract from the Hanle effect. In comparison, in bulk GaAs channels lifetimes $>1$ ns have been measured [34]. The reduction in spin lifetime is likely to be due to an excess number of dopants in the sample. Reference [35] has shown that higher doped p–i–n junctions have reduced spin efficiency due to the creation of a population of unpolarized carriers in the quantum well. This gives rise to extra electron–electron scattering and means that not all of the recombinating electrons come from the polarized injecting source. The samples studied have considerably more doping than the high doped LEDs in reference [35]. Whereas in reference [35] devices consist of a highly doped injector followed by 150 nm of material doped at $1 \times 10^{17}$ cm$^{-3}$, the devices studied here have 100 nm of $1 \times 10^{18}$ cm$^{-3}$ after the injector in these samples, a factor of 6 higher. An excess of electrons in the well is also consistent with a D’yakonov–Perel’ scattering mechanism, which is dominant for doped n-type semiconductors [36, 37]. The high doping in these samples was also partly responsible for the creation of a potential minimum near the Schottky barrier in devices made from the same semiconductor wafer, albeit due to growth variations across the wafer. Recombination from this region was shown to be highly dependent on the sample bias, which would cause a change in the unpolarized electron population at this minimum [14]. The large carrier density in the well would also favour band-to-band rather than excitonic recombination [30].
5. Summary

InGaAs-based spin-LEDs with in situ grown Fe spin-injectors were measured in both the Faraday and Hanle geometries. In the Faraday geometry a polarization of 4.5 ± 1% was measured at 4 K, which was shown to be consistent with a peak optical polarization of 1.5% measured in the Hanle geometry. The Hanle effect experimental data also provided the spin lifetime as a function of temperature, which was seen to remain constant at around 30 to 40 ps from 4 K to ambient temperature, consistent with a D’yakonov–Perel’ type model for a 2D system. The low electron spin-polarization seen in these samples can be explained by an excess of n-type dopants in the p–i–n junction which leads to population of the quantum well by unpolarized electrons.

Here we see that although most of the effort in semiconductor spintronics devices has been on improving the spin-injecting contact, optimization of the semiconductor is also required. Conventional band structure modelling of the semiconductor devices is not able to capture the full range of effects that may reduce the spin-polarisation efficiency in the semiconductor, however in situ wafer transfer is essential in reducing the impact of defects and impurities at the interface as a starting point.

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