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Abstract

A magnetic tunnel transistor is used to electrically inject spin-polarized hot electrons into a multi GaAs/$In_{0.2}Ga_{0.8}As$ quantum well light-emitting diode. Electroluminescence (EL) from the quantum wells shows a polarization of ~ 10% after subtraction of a linear background polarization, indicating successful injection of hot electron spins into semiconducting GaAs. The EL polarization shows a strong dependence on the bias voltage across the light emitting diode, which may originate from changes in the electron spin relaxation rate in the quantum wells under different bias conditions.

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The vision of spin-based electronics has inspired much research on the transport and manipulation of spins in semiconductors and metals[1]. The long spin lifetimes and the possibility to transport spins coherently over large distances in semiconductors[2, 3] promises a new generation of microelectronic devices based on the spin degree of freedom[4-7]. Efficient electrical injection of spin polarized electrons into semiconductors is one of the key issues for successful development of these devices. Electrical injection of spin polarized electrons has been demonstrated with diluted magnetic semiconductors (DMS)[8-10]. However, the low Curie temperatures of known DMS materials means that it is not currently possible to achieve spin injection at room temperature. Ferromagnetic (FM) metals are attractive as spin injectors due to their high Curie temperatures. But so far, direct electrical spin injection from FM metals into semiconductors shows low efficiency[11-13] and, in any case, may be fundamentally limited by the conductivity mismatch between metals and semiconductors[14].

Recently, FM metal/tunnel barrier contacts have been used for spin injection[15-19]. In these experiments, spins are injected at energies close to the Fermi energy in the metal injector. An alternative approach is to use a magnetic tunnel transistor (MTT)[20-23] as the spin injector. The MTT is an interesting hybrid spintronic device merging conventional magnetoelectronic and semiconducting components. Within the MTT, electron transport across the metallic base layer occurs at energies ~ 1-2 eV above the Fermi energy of this region. The electron energy can be adjusted by controlling the bias voltage across the tunnel barrier, enabling the study of hot electron spin transport and relaxation at various energies. Since the MTT injects hot electrons ballistically into the semiconductor through a tunnel barrier the device overcomes the conductivity mismatch problem[24]. Thus, the injected electrons should, in principle, retain their spin polarization in the semiconductor. Moreover, efficient spin filtering in the ferromagnetic base layer of the MTT leads to a highly spin-polarized current at the base/collector interface, making the MTT a promising candidate as a spin injector which is tunable in both energy, and magnitude and sign of the spin of the electron.

The MTT is a three-terminal device combining a magnetic tunnel junction (MTJ) with a semiconductor collector as shown schematically in Fig. 1. A FM metal emitter injects spin-polarized hot electrons across the tunnel barrier into a FM metal base. These hot electrons traverse the base layer and are subsequently collected by the collector. Spin-dependent scattering in the base layer causes the electrons to lose energy and/or change momentum. Only electrons that maintain enough energy to surmount the Schottky barrier at the base/collector interface and that can find available states in the conduction band of the semiconductor collector are collected. As a result, the transmission of hot electrons into the collector is very sensitive to scattering processes in the base layer. Due to a large asymmetry in the majority and minority electron attenuation lengths in the base layer, majority electrons are preferentially collected. The hot electron current can be more than 95% spin polarized at the base/collector interface[23]. However, the degree of spin polarization that can be maintained after the electrons cross the metal/semiconductor interface remains an important question. In order to measure the spin injection efficiency, a quantum well (QW) light-emitting diode (LED) is incorporated as the collector of the MTT. The injected electrons recombine with holes in the QW and emit photons. The polarization of emitted light is correlated to the spin polarization of the electrons according to the optical selection rules[25, 26].

The semiconductor LED structure is grown by molecular beam epitaxy (MBE). Three p-$Al_{0.32}Ga_{0.68}As$ layer layers (total thickness 780 nm) with stepped doping concentration are grown on a Be doped p-GaAs substrate, followed by a 60 nm thick undoped $Al_{0.32}Ga_{0.68}As$ layer. Three GaAs/$In_{0.2}Ga_{0.8}As$ QWs are grown on top of the $Al_{0.32}Ga_{0.68}As$ layers with a well width of 8 nm and a barrier layer width of 15 nm. Another thin undoped $Al_{0.32}Ga_{0.68}As$ layer (5nm) is then grown on top of the QWs. Finally, 100 nm n-GaAs (with a doping concentration of $\sim 5\text{x}10^{16}$ cm^{-3}) is grown as the top layer to form a Schottky barrier with the FM base. The doping concentration of this top layer is optimized for the desired Schottky barrier characteristics. The $Al_{0.32}Ga_{0.68}As$ layers on both sides of the QWs help to confine electrons and holes within the wells to promote recombination i.e. the $Al_{0.32}Ga_{0.68}As$ layers on the bottom prevent hot electrons from traveling deep into the p-layer, while the thin upper $Al_{0.32}Ga_{0.68}As$ layer prevents holes from traveling into the lightly doped n-layer. The $Al_{0.32}Ga_{0.68}As$ layers on the substrate side also prevent the Be dopants from diffusing into the QW region. Finally, a low temperature arsenic cap layer is deposited on the top surface to prevent oxidation and to protect the top surface after it is removed from the MBE chamber. After the MBE growth, the sample is transferred in air to an ultra-high-vacuum sputtering chamber, where it is first heated up to ~520 °C to remove the arsenic cap. The sample is then cooled to room temperature and an MTJ is then deposited on the semiconductor LED with DC magnetron and/or ion beam sputtering. A sequence of three shadow masks are used to form the base layer, the emitter isolation pads and the emitter layer respectively[22, 23]. The base layer consists of 3.5 nm of $Ni_{81}Fe_{19}$ and 1.5 nm $Co_{84}Fe_{16}$. The Al_2O_3 tunnel barrier is formed by reactive sputtering of Al in the presence of oxygen. The thickness of the barrier is ~2.2 nm. The emitter consists of 5 nm $Co_{84}Fe_{16}$. A 5 nm thick Ta layer is used as the cap layer to prevent oxidation of $Co_{84}Fe_{16}$.

The MTT is placed in a superconducting magnet cryostat with optical access for spin polarized luminescence measurements. A magnetic field perpendicular to the FM layers is applied to rotate their magnetic moments out of the plane. The luminescence experiments are conducted in the Faraday geometry with the propagation direction of the light parallel to the magnetic field. The emitter/base bias voltage (V_{EB}) determines the energy of the injected electrons, while the collector/base bias voltage (V_{CB}) is used to adjust band-bending of the LED (Fig. 1). A particular advantage of using InGaAs wells is that the QW luminescence energy is smaller than the GaAs bandgap energy so the substrate is transparent and the electroluminescence (EL) from the quantum wells can be collected through the substrate. This minimizes any possible magnetic circular dichroism arising from polarization-dependent transmission through the FM layers. A combination of a liquid crystal retarder and a linear polarizer is used to selectively analyze the circular polarization components of the emitted light as σ+ (left hand) or σ- (right hand). The spectrum of the selected component is measured with a grating spectrometer and a charge-coupled device.

The EL shown in Fig. 2 is measured with V_{EB} = -2.06 V and V_{CB} = 1.0 V at 1.4 K. The solid and open circles represent σ+ and σ- polarization components respectively. Note that the width of the EL peaks is only ~ 2.5 nm which is limited by the spectrometer resolution for the given signal level. According to absorption studies, the separation in wavelength between electron recombination with heavy holes and with light holes is ~ 40 nm in 8nm wide $In_{0.2}Ga_{0.8}As$ QWs. Therefore, the narrow EL line width enables the unambiguous detection of electron-heavy hole recombination. In this case, the optical selection rules are very simple: the polarization of light is equal to the polarization of electron spins just before recombination [25, 26]. The polarization of EL clearly depends on the magnetic field. At zero field, the intensities of σ+ (I^+) and σ- (I^-) components are the same. At high fields, there is a significant difference between I^+ and I^-. The polarization of EL, defined as $P_{EL} = (I^+ - I^-) / (I^+ + I^-)$ is ~ 13% at 2.5 T and ~ –13% at –2.5 T. The sign of P_{EL} indicates injection of majority electron spins (-1/2 spin state) into the QWs. This result is consistent with the sign of collector current polarization observed in electrical transport measurements in similar MTTs[22,23]. Excitons in $In_{0.2}Ga_{0.8}As$ have a large g-factor, leading to a large Zeeman splitting energy in the QWs, which is shown by the shift of the EL peak center positions for σ+ and σ- components at high fields. The overall intensity of EL at zero field is smaller than that at high fields. The origin of this field dependence is unclear at present. It may result from a change of recombination efficiency and/or spin relaxation rate in the QWs caused by the magnetic field.

In Fig. 3(a), P_{EL} is measured as a function of magnetic field under the same bias conditions as described above. P_{EL} increases rapidly with magnetic field up to ~ 2 T, where the magnetic moments of the FM emitter and base layers are expected to be completely rotated out of plane by the field. Above 2 T, P_{EL} still increases with the field. This is mainly due to the background polarization caused by thermalization of the exciton spins in the magnetic field. The polarization P_C obtained after subtracting this linear background polarization from P_{EL} is shown in Fig. 3(b). A value of P_C ~ 10% is obtained at 2.5 T. Note that polarization dependent reflection at the FM base/GaAs interface may give rise to a contribution to the EL polarization. However, we find that this effect is very small (<1%) by passing linearly polarized light through the backside of the wafer and measuring the polarization of light reflected from the FM layers. The dashed line in Fig. 3(b) shows the magnetization of the FM layers measured with a SQUID magnetometer at 10 K for field oriented perpendicular to the sample. The field dependence of the sample magnetization is in excellent agreement with the field dependence of P_C confirming that P_C is related to the injection of spin polarized hot electrons from the MTT injector.

Fig. 4(a) summarizes the collector/base bias dependence of P_{EL} measured at 2.5 T. P_{EL} first decreases with increasing bias, changes sign for V_{CB} ~ 1.4 V, then stays approximately constant at higher bias voltages. This bias dependence may be caused by a change of the spin relaxation rate in the QWs under different bias conditions. Increasing V_{CB} results in an increasing hole current flowing from the p-GaAs substrate into the QWs (see the inset of Fig. 4(a)). Electron-hole interactions can result in electron spins relaxing to the +1/2 state through the Bir-Aronov-Pikus (BAP) mechanism[25]. When the hole concentration is low, the spin relaxation rate is proportional to the number of holes in the QWs. The EL polarization therefore is expected to decrease with increasing bias. However, above a certain critical hole concentration, the increase of the spin relaxation rate slows down because of the decrease of the Sommerfeld factor due to screening by the holes[25]. Consequently, the EL polarization does not decrease further with increasing bias. Other spin relaxation processes could also be influenced by the bias. For example, spin relaxation through the D'yakonov-Perel' (DP) mechanism is very sensitive to hot electron energy[25]. At high bias, the conduction band of the n-GaAs region bends down more and the injected hot electrons would need to lose more energy to reach the bottom of the conduction band. During this process, they are more likely to lose their original spin orientation.

The bias dependence of the EL intensities at 2.5 T is summarized in Fig. 4(b). Increasing bias brings more holes into the QWs. As a result, electron-hole recombination becomes more efficient and the EL intensities go up with bias. However, when the bias is above ~1.4 V, there are already enough holes in the QWs. Recombination is now limited by the number of electrons injected into the QWs and the total EL intensity stays approximately constant. Meanwhile, the intensity of the $\sigma+$ component decreases significantly due to spin relaxation to the +1/2 state before recombination. This leads to the negative EL polarization at high biases.

The spin splitting in the GaAs conduction band is proportional to $E^{3/2}$, E being the electron energy. As a result, the DP mechanism becomes very effective at elevated electron energies[25]. The injected hot electrons lose a significant amount of polarization during the process of thermalization to the bottom of the conduction band. The efficiency of the DP mechanism increases rapidly with temperature[25], which limits reliable measurements of electrically injected hot electron spin polarization at higher temperatures. After the hot electrons enter the QW region, further spin relaxation can occur in the QWs before recombination[27]. The measured EL polarization indicates the electron spin polarization right before recombination with holes and, therefore, sets a lower bound on the spin-injection efficiency. It would be interesting to use other semiconductor collectors (e.g. Si or GaN), where the DP mechanism is not so important[25, 28, 29]. Under these circumstances, not only should the measured spin polarization be greatly improved but reliable measurements at much higher temperatures would then be possible.

In summary, we have demonstrated that the hot electron current injected from an MTT retains its polarization in the GaAs heterostructure collector, even though the injected electrons have high energy of ~ 2 eV above the Fermi energy. An electron spin polarization of ~ 10% is inferred from the spin-polarized electroluminescence of a GaAs/$In_{0.2}Ga_{0.8}As$ light emitting diode. We find that the polarization of the EL is very sensitive to the collector/base bias voltage. These studies set a lower bound on the spin injection efficiency because of likely electron spin relaxation before recombination in the quantum wells. The MTT is a unique tool to study hot electron spin transport and relaxation in semiconductors. The energy dependence of hot electron spin injection is an interesting topic for future experiments.

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Fig. 1 The schematic band diagram of the MTT with a QW LED collector. The emitter/base bias V_{EB} controls the energy of injected hot electrons. The collector/base bias V_{CB} can be used to adjust band bending of the LED.

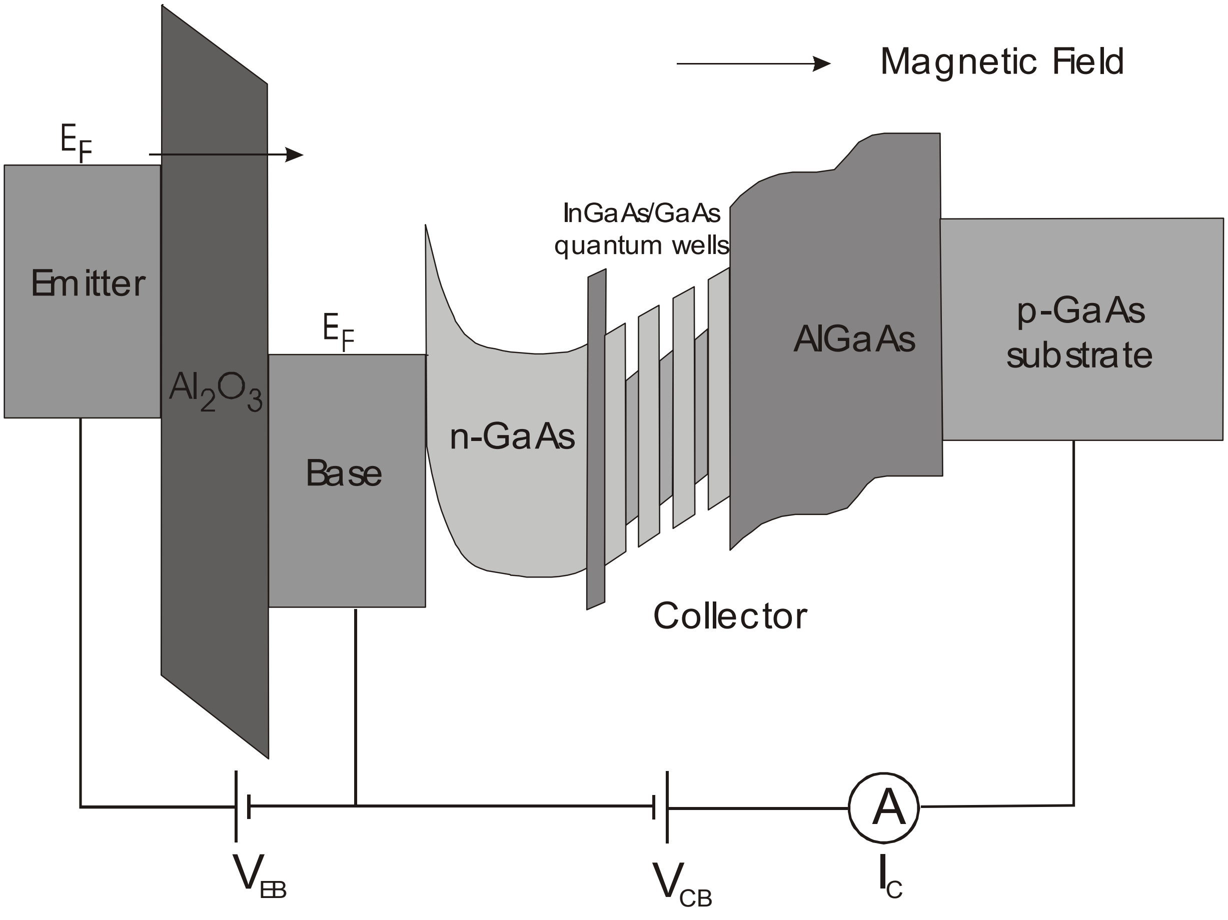

Fig. 2 EL measured in magnetic fields of 2.5 T, 0 and –2.5 T at 1.4 K. The solid and open circles represent σ+ and σ- polarization components respectively. The bias conditions are: V_{EB} = -2.06 V, V_{CB} = 1.0 V.

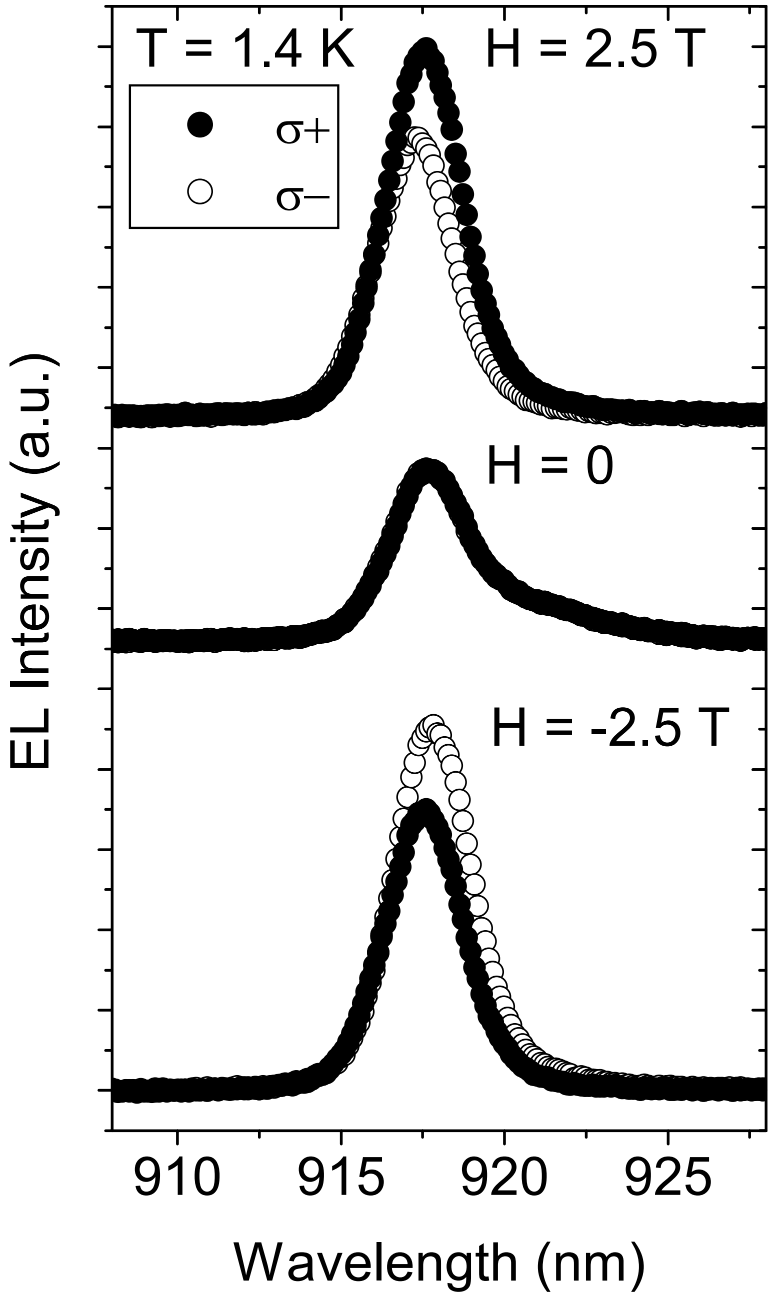

Fig. 3 The measured EL polarization (a) and the polarization after subtracting a linear background (b) as a function of magnetic field at 1.4 K. The bias conditions are the same as those in Fig. 2. The dashed line in (b) shows the magnetic moments of the FM layers measured with a SQUID magnetometer at 10 K.

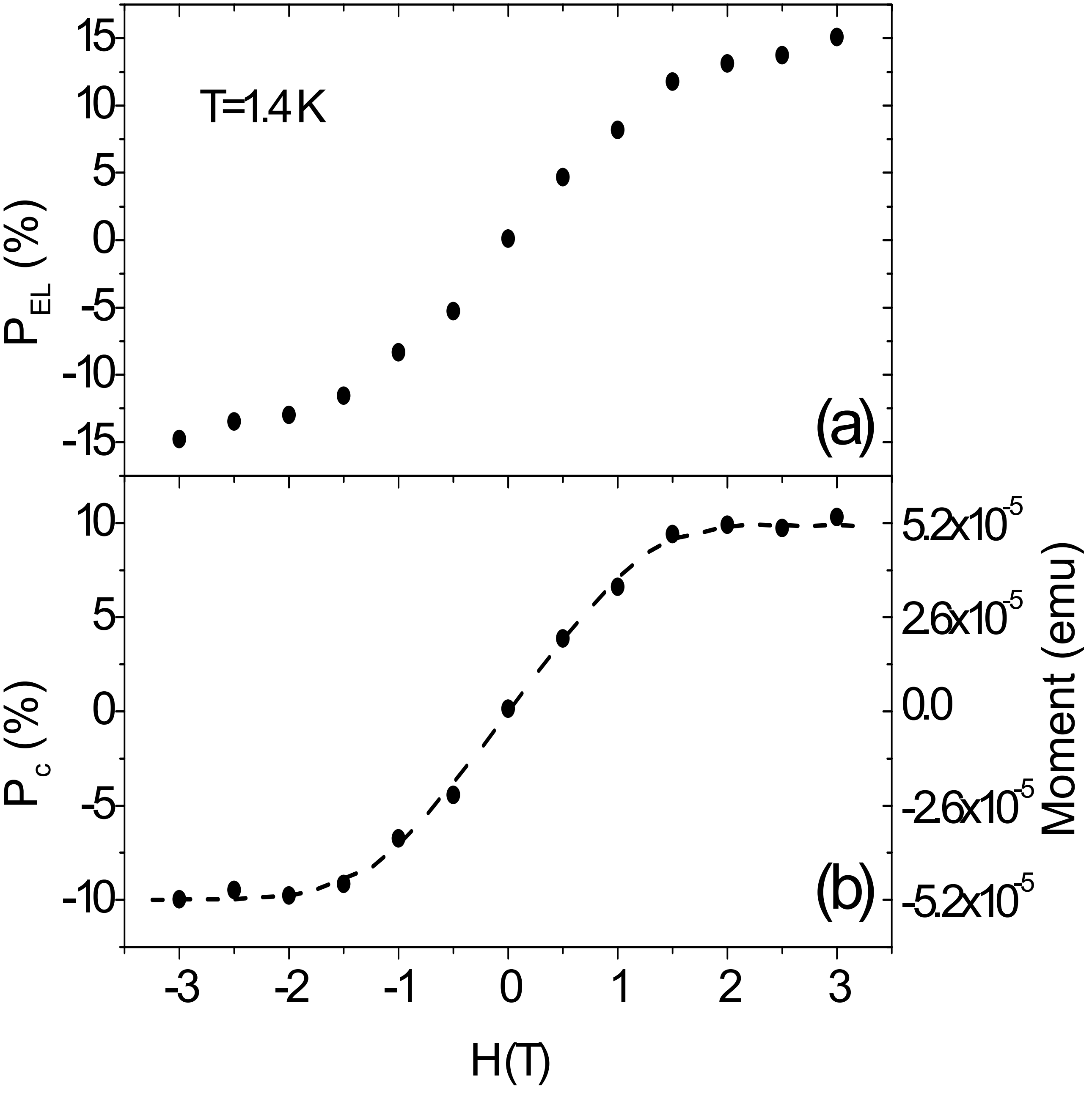

Fig. 4 The collector/base bias dependence of EL polarization (a) and intensities (b) at 2.5 T. The inset in (a) shows the hole current as a function of V_{CB}. The emitter/base bias is V_{EB} = -2.06 V.