Tunnel spin polarization of $Ni_{80}Fe_{20}/SiO_2$ probed with a magnetic tunnel transistor

B. G. Park, T. Banerjee, B. C. Min, J. C. Lodder, and R. Jansen
MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands
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The tunnel spin polarization of $Ni_{80}Fe_{20}/SiO_2$ interfaces has been investigated using a magnetic tunnel transistor (MTT). The MTT with a $Ni_{80}Fe_{20}/SiO_2$ emitter shows a magnetocurrent of 74% at 100 K, corresponding to a tunnel spin polarization of the $Ni_{80}Fe_{20}/SiO_2$ interface of 27%. This is only slightly lower than the value of 34% for $Ni_{80}Fe_{20}/Al_2O_3$ interfaces determined in similar MTT structures. This suggests that SiO_2 can be applied in semiconductor spintronic devices, for example in ferromagnet/SiO_2/Si tunnel contacts for spin injection.

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I. INTRODUCTION

Spin-polarized tunneling of electrons in ferromagnet (FM)/insulator (I) heterostructures has been extensively studied because it determines the tunnel magnetoresistance of a magnetic tunnel junction.[1–4] The tunnel spin polarization is not an intrinsic property of the FM layer, but is also dependent on interfacial properties and the choice of a tunnel barrier. The amplitude of the tunnel spin polarization and even its sign can be altered by changing the adjacent oxide barrier.[5,6] Recently, it has been reported that a tunnel spin polarization of about 80% is achieved for transition metals such as CoFe or Fe when crystalline MgO is introduced as a tunnel barrier.[7,8] Spin-polarized tunneling from FM/I contacts also draws much attention in the semiconductor spintronics technology as it can be used in a spin injection device of a ferromagnet/insulator/semiconductor structure,[9,10] where the tunnel barrier is introduced in order to overcome the conductance mismatch between a ferromagnetic metal and a semiconductor.

The standard technique for probing the tunnel spin polarization of a FM/I interface was developed by Meservey and Tedrow.[1] This technique is constrained to low temperatures (less than 1 K) because a superconductor is used as an electrode into which electrons tunnel. In this work, we have used an alternative method to probe the tunnel spin polarization of a FM/I interface using a magnetic tunnel transistor (MTT). The MTT is a three-terminal hybrid device consisting of a tunnel emitter, a FM base, and a semiconductor collector.[11,12] In a MTT with a FM emitter and a base with a single FM layer, spin-polarized hot electrons are injected into the base by tunneling. After spin-dependent scattering in the FM base, they are collected in the conduction band of the semiconductor, provided they have the right energy and momentum to overcome the Schottky barrier formed at the base/collector interface. The magnetic response of the MTT, the so-called magnetocurrent (MC), is determined by the spin-polarized tunneling from the emitter and by spin-dependent transmission in the FM base.[13] Since the MC depends on the tunnel spin polarization and the MTT operates with a typical emitter bias of the order of 1 V and at finite temperature, the MTT can be used to study the spin polarization of ferromagnet/insulator interfaces at high bias voltage and finite temperature. In our previous work, the tunnel spin polarization of $Ni_{80}Fe_{20}/Al_2O_3$ interfaces at an emitter bias of 1 V was measured in the temperature range from 100 K to room temperature.[14] In this work, we have fabricated a MTT with a composite Al_2O_3/SiO_2 tunnel barrier and investigated the tunnel spin polarization of the $Ni_{80}Fe_{20}/SiO_2$ interface (see Fig. 1). Since SiO_2 is widely used as a gate oxide and the growth of SiO_2 on top of Si is well established in semiconductor technology, SiO_2 is a potential candidate as a tunnel barrier in Si-based spintronic devices such as FM/SiO_2/Si tunnel contacts for spin injection. However, reports on the tunnel spin polarization of FM/SiO_2 interfaces are rare,[15,16] and a tunnel magnetoresistance (TMR) of only 4% was reported in a magnetic tunnel junction (MTJ) with a SiO_2 barrier. This is quite a low value as compared to that of MTJs with other tunnel barriers such as Al_2O_3 or MgO. The low TMR in the MTJ with a SiO_2 tunnel barrier is not clearly understood. It could be due to an intrinsic low tunnel spin polarization of the FM/SiO_2 interface, or due to a materials issue such as silicide formation during the fabrication process. Here, it is shown that a MTT with a $Ni_{80}Fe_{20}/SiO_2$ emitter exhibits a magnetocurrent (MC) of 74% at an emitter

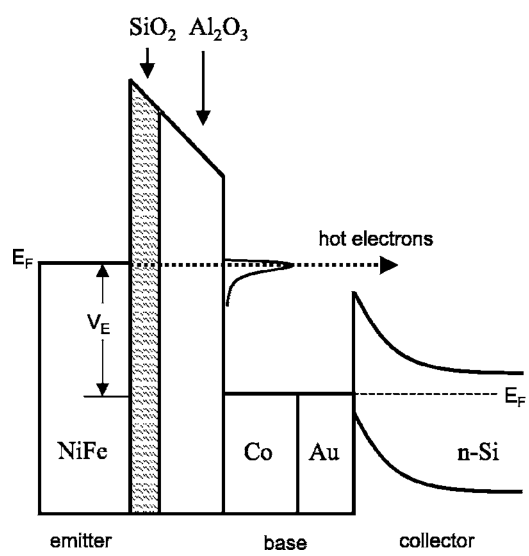

FIG. 1. Schematic energy diagram of a MTT with a composite Al_2O_3/SiO_2 tunnel barrier, in which the tunnel spin polarization of the emitter is determined by the $Ni_{80}Fe_{20}/SiO_2$ interface.

TABLE I. Summary of thickness and oxidation time (t_{ox}) for each composite tunnel barrier.

Series	Al thickness	t_{ox}	Si thickness	t_{ox}
1	2.4 nm	15 min		
2	1.2 nm	7 min	0,0.2,0.4 nm	5 min
3	0.8 nm	3 min	0.2,0.4,0.6 nm	5 min
4	0.3 nm	0 min	0.6 nm	5 min

bias of −1 V and 100 K, which corresponds to a tunnel spin polarization of 27% for the $Ni_{80}Fe_{20}/SiO_2$ interface. This demonstrates that electrons tunneling from the $Ni_{80}Fe_{20}/SiO_2$ interface are intrinsically highly spin polarized.

II. EXPERIMENTS

Samples were deposited by *e*-beam evaporation in a molecular beam epitaxy system at a base pressure of 10^{-10} mbar. The structure of the MTT was *n*-type Si/Au (7 nm)/Co (8 nm)/$Al_2O_3/SiO_2/Ni_{80}Fe_{20}$ (10 nm)/Au (10 nm). The films were grown on a lithographically defined area of an *n*-type Si wafer, surrounded by a thick SiO_2 to reduce the device size and eliminate edge leakage currents across the collector diode. A high quality Schottky barrier of 0.8 eV was formed at the interface between an *n*-type Si substrate and an Au layer. The leakage current across the collector diode is less than 0.2 pA at a temperature of 100 K. The composite tunnel barrier of Al_2O_3/SiO_2 was formed by a double step process. Since the MC depends on the tunnel spin polarization of the emitter interface, we introduced a SiO_2 barrier at the emitter interface only and kept the base interface of Al_2O_3/FM to avoid any possibility of silicide formation. First, an Al_2O_3 barrier was formed by plasma oxidation of an Al layer of thickness between 0.3 and 2.4 nm. Then, a thin Si layer of 0.2 to 0.6 nm was deposited and then plasma oxidized to form a composite Al_2O_3/SiO_2 tunnel barrier. The oxidation conditions for each tunnel barrier are summarized in Table I. The barrier thicknesses as mentioned here are as-deposited layer thicknesses, prior to oxidation. After oxidation, the SiO_2 would be about two times thicker than the as-deposited Si layer while the thickness of Al_2O_3 increases by about 25%.[17] MTT devices were fabricated using standard photolithography, ion beam etching, and lift-off techniques. The diameter of the junction area varied from 10 to 100 μm and that of the base-collector diode from 20 to 130 μm. Transport measurements were conducted using a four-point geometry for the emitter to base tunnel junction and a separate ohmic contact to the back of the Si collector at a temperature of 100 K.

III. RESULTS AND DISCUSSIONS

The collector current (I_C) as a function of emitter bias voltage for a MTT with an Al_2O_3 (0.8 nm)/SiO_2 (0.6 nm) tunnel barrier is shown in the top panel of Fig. 2. The curve labeled P state (AP state) is obtained in a magnetic field of −100 Oe (+17 Oe), corresponding to a parallel (antiparallel) alignment of the Co and $Ni_{80}Fe_{20}$ magnetizations. The I_C abruptly increases with emitter bias voltage at an onset voltage of 0.8 V that corresponds to the barrier height of the Au/*n*-Si collector Schottky diode. I_C for the parallel alignment is larger than that for an antiparallel alignment. To clearly see the magnetic field dependence, the I_C was measured at a bias voltage of −1 V while sweeping the magnetic field (middle panel of Fig. 2). There are two current levels depending on the external magnetic field. At large magnetic fields, the two magnetic layers have their magnetization directions aligned parallel. This gives the largest I_C of 78.5 pA. When the magnetic field is reversed and reaches a field region where the magnetizations of two FM layers are antiparallel, the I_C reduces to 45.0 pA. This results in a MC of 74%. Here, MC is defined as $(I_C^P - I_C^{AP})/I_C^{AP}$, where *P* and *AP* refer to the parallel and antiparallel alignment of two magnetic layers, respectively. The MC of a MTT with a composite Al_2O_3/SiO_2 barrier is lower than the MC of 95% of a MTT with 2.4 nm thick Al_2O_3, which is shown in the bottom panel of Fig. 2. The switching field of the Co layer in the MTT with the Al_2O_3/SiO_2 barrier is larger than that with the Al_2O_3 barrier. This could be due to the Co oxide formation at the interface with the tunnel barrier because of over-oxidation.

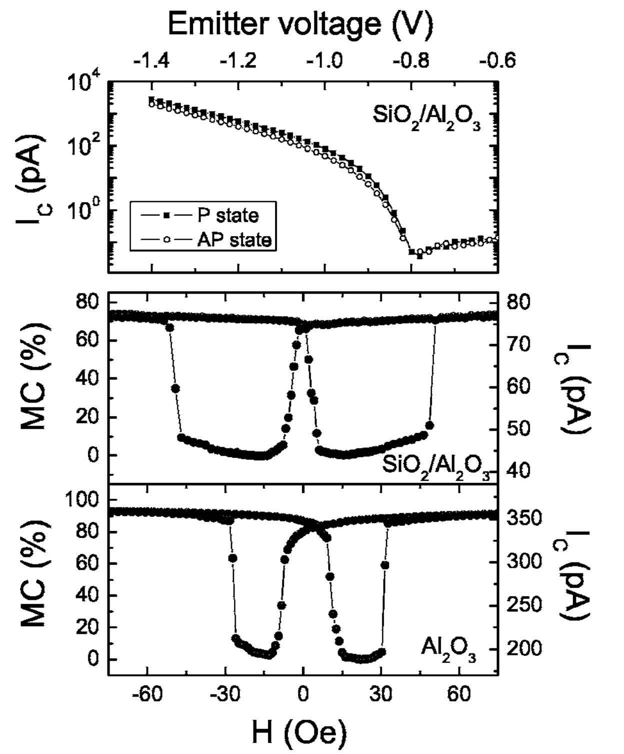

FIG. 2. Characteristics of a MTT with the structure Si/Au (7 nm)/Co (8 nm)/Al_2O_3 (0.8 nm)/SiO_2 (0.6 nm)/$Ni_{80}Fe_{20}$ (10 nm) / Au (10 nm). Top panel: Collector current as a function of emitter bias voltage for parallel (*P*) and antiparallel (*AP*) alignment of the $Ni_{80}Fe_{20}$ and Co magnetization. Middle and bottom panel: Magnetocurrent for a MTT with an Al_2O_3 (0.8 nm)/SiO_2 (0.6 nm) tunnel barrier and an Al_2O_3 barrier, respectively, at a bias voltage of −1 V and 100 K.

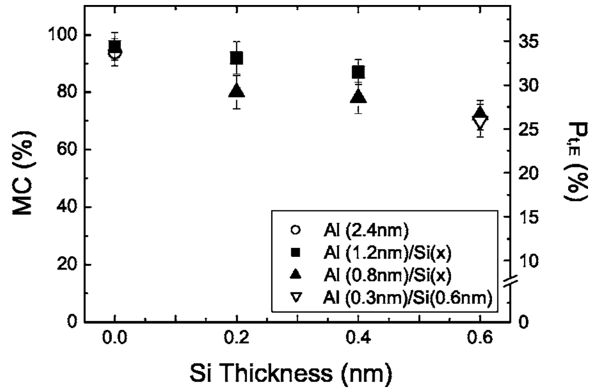

FIG. 3. Magnetocurrent and corresponding tunnel spin polarization of the $Ni_{80}Fe_{20}/SiO_2$ interface as a function of Si thickness prior to oxidation into SiO_2. Symbols represent the four different Al layers with thicknesses from 0.3 to 2.4 nm, with oxidation time given in Table I. The measurements were done at 100 K and an emitter bias of −1 V.

The tunnel spin polarization can be extracted from the MC value.[13,14] The MC of a MTT with a ferromagnetic emitter is determined by spin-dependent tunneling from the emitter and spin-dependent transport of hot electrons in the base. The MC can be expressed as follows:

$$MC = \frac{2P_{t,E}T_B}{1 - P_{t,E}T_B}, \tag{1}$$

where $P_{t,E}$ is the tunnel spin polarization from the emitter and T_B is the spin asymmetry in the base transmission, defined as follows:

$$T_B = \frac{\delta^M \exp(-t/\lambda^M) - \delta^m \exp(-t/\lambda^m)}{\delta^M \exp(-t/\lambda^M) + \delta^m \exp(-t/\lambda^m)}. \tag{2}$$

Here, δ^M and δ^m are the number of majority and minority tunnel electrons associated with the I/base interface, t is the FM base layer thickness, and λ^M and λ^m are the hot-electron attenuation lengths for the majority and minority spins in the FM base.

Since the attenuation length of the majority spin hot electrons is considerably larger than that of minority spins,[18–20] at large base thickness only majority spins can be transmitted ($T_B \sim 1$), and the MC is saturated at a value of $2P_{t,E}/(1-P_{t,E})$ and is dependent only on the tunnel spin polarization. This allows the MTT to be used to probe the tunnel spin polarization of FM/I interfaces.

Figure 3 shows the MC and corresponding tunnel spin polarization of the emitter interface at 100 K as a function of Si thickness for a MTT with a composite Al_2O_3/SiO_2 oxide. In the graph, symbols represent the four different Al layers with thickness ranging from 0.3 to 2.4 nm. As the Si thickness is increased from zero to 0.6 nm, the MC decreases from 95 to 74%. Since only majority electrons are transmitted through an 8 nm Co base layer due to the large asymmetry of the hot-electron attenuation length between majority and minority spin electrons,[20] the MC value only depends on the tunnel polarization of the emitter interface. The tunnel spin polarization extracted from the MC values decreases from 34 to 27% with increasing SiO_2 thickness. This shows that electrons tunneling from the $Ni_{80}Fe_{20}/SiO_2$ interface are highly spin polarized even though the spin polarization is slightly lower than the value of 34% for a $Ni_{80}Fe_{20}/Al_2O_3$ interface.

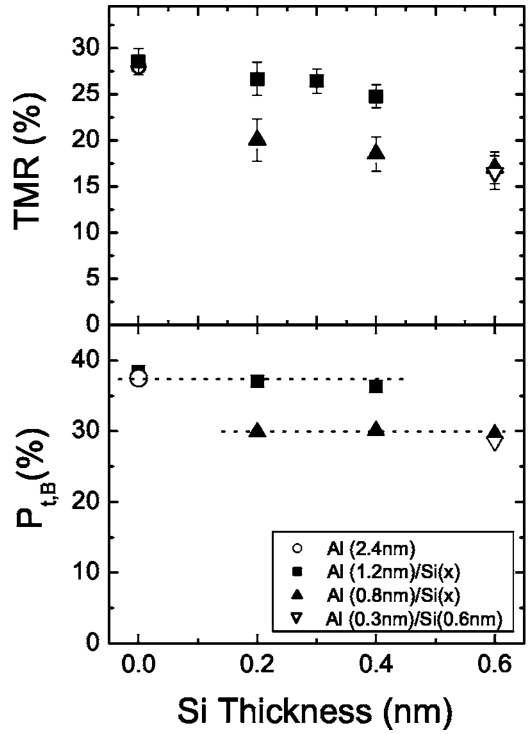

FIG. 4. Top panel: Tunnel magnetoresistance as a function of Si thickness prior to oxidation into SiO_2 in junctions with a composite Al_2O_3/SiO_2 oxide using the same structures as in Fig. 3. The measurements were done at 100 K and a bias voltage of 20 mV. Bottom panel: Tunnel spin polarization of the base/Al_2O_3 interface as determined from TMR (top panel) and $P_{t,E}$ (Fig. 3), as explained in the text.

The MTT can also be used to obtain the tunnel magnetoresistance (TMR) of the emitter/insulator/base tunnel junction. The TMR measurements were done at a bias voltage of 20 mV and 100 K. The results are shown in the top panel of Fig. 4. The TMR decreases from 27 to 17% as the Si thickness is increased from zero to 0.6 nm. Whereas the reduction of the MC is due to the decrease of the tunnel spin polarization of the emitter interface, the TMR ratio is determined by the product of the tunnel spin polarization of bottom and top FM interfaces. Using the Juliere model[21] [$TMR = 2P_{t,E}P_{t,B}/(1-P_{t,E}P_{t,B})$], where $P_{t,E}$ and $P_{t,B}$ are the tunnel spin polarization of the emitter (top) and base (bottom) FM interfaces, respectively, the tunnel spin polarization of the base interface ($P_{t,B}$) can be extracted from the TMR and the spin polarization values of the emitter interface ($P_{t,E}$). The latter can be obtained from the MC. Even though the MC was measured at the bias voltage of −1 V, the extracted $P_{t,E}$ represents the tunnel spin polarization of the states near the Fermi level because most of the tunnel electrons contributing to the MC come from those states. The tunnel electrons from the states away from the Fermi level are filtered out at the Schottky barrier of the collector. Therefore, the $P_{t,E}$ values shown in Fig. 3 are applicable to calculate the $P_{t,B}$ with the TMR measured at a low bias voltage. The results are shown in the bottom panel of Fig. 4. The figure shows that the tunnel spin polarization of the bottom Co interface is independent of the SiO_2 thickness. This is expected because the bottom interfaces are the same Co/Al_2O_3 contact regardless of the SiO_2 thickness. This indicates that there is no significant intermixing or structural relocation of the oxide layers during the oxidation process. The tunnel spin polarization of the bottom interface is 37% for junctions with 2.4 and 1.2 nm Al layers. However, it reduces to 30% for junctions with 0.8 and 0.3 nm Al layers. If the Al layer is thin, the Co base layer underneath can be partially oxidized during the plasma oxidation. This overoxidation causes the lower tunnel spin polarization of the bottom interfaces for junctions with a thin Al layer. This may also be responsible for the increase of the switching field of the Co layer as shown in Fig. 2.

The large tunnel spin polarization values obtained here may appear at odds with the absence of large TMR in MTJs with SiO_2 barriers. To gain more insight, we have also fabricated MTTs with a pure SiO_2 barrier. Si layers of 1.5 $\sim$2.5 nm were deposited on top of the Co base and subsequently oxidized in the oxygen plasma. Such MTTs showed a similar tunnel junction resistance and collector current to that of MTTs with the Al_2O_3/SiO_2 composite barrier. However, there was no magnetic field dependence of the junction resistance or the collector current. This can be explained by Co-silicide formation during the deposition or the oxidation process. The Co-silicide induces paramagnetic defects in the tunnel barrier or at the interfaces with the FM layers. Such defects act as scattering centers for spins, resulting in no magnetic response. We therefore believe that silicide formation is responsible for the low TMR in the MTJ with the SiO_2 barrier, instead of an intrinsically low tunnel spin polarization.

IV. CONCLUSIONS

We have investigated the tunnel spin polarization of a $Ni_{80}Fe_{20}/SiO_2$ interface using a magnetic tunnel transistor. The tunnel spin polarization of the $Ni_{80}Fe_{20}/SiO_2$ interface is 27% at 100 K, which is only slightly lower than that of the $Ni_{80}Fe_{20}/Al_2O_3$ interface. This demonstrates that the low TMR in a MTJ with a SiO_2 barrier is not due to an intrinsic low tunnel spin polarization of the $Ni_{80}Fe_{20}/SiO_2$ interface, but due to a materials issue such as silicide formation. Therefore, SiO_2 can be applied in semiconductor spintronic devices, for example in devices that use $FM/SiO_2/Si$ tunnel contacts for spin injection.

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