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► **To cite this version:**

Yuan Lu, Daniel Lacour, G. Lengaigne, S. Le Gall, S. Suire, et al.. Interfacial trapping for hot electron injection in silicon. *Applied Physics Letters*, 2013, 103 (2), 10.1063/1.4813015 . hal-01276612

**HAL Id: hal-01276612**

**<https://hal.science/hal-01276612>**

Submitted on 3 Aug 2024

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RESEARCH ARTICLE | JULY 10 2013

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*Appl. Phys. Lett.* 103, 022407 (2013)


<https://doi.org/10.1063/1.4813015>





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## Interfacial trapping for hot electron injection in silicon

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(Received 6 May 2013; accepted 17 June 2013; published online 10 July 2013)

We have evidenced a new interfacial trapping phenomenon for hot electron injection in silicon by studying magnetic tunnel transistors (MTTs) with a MgO tunneling barrier emitter and a Cu/Si Schottky barrier collector. Transport measurements on hot electrons indicate that an interfacial charge trapping and a backscattering-induced collector current limitation take place with the MTT spin-valve base both in parallel and antiparallel states when the temperature is lower than 25 K, which results in a rapid decrease of the magnetocurrent ratio from  $\sim 2000\%$  at 25 K to  $800\%$  at 17 K. The binding energy of the trapped electron is estimated to be about 1.7 meV, which is also found to increase with the magnetic field. A simple analytic model considering the interfacial electron trapping and releasing is proposed to explain the experimental results. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4813015>]

Hot electron injection is a good way to overcome the impedance mismatch between metals and semiconductors to achieve efficient spin injection into the semiconductor.<sup>1,2</sup> When the kinetic energy of electrons in the metal is higher than the Schottky barrier height (SBH), they can be ballistically injected into the semiconductor. By combining giant magnetoresistance (GMR) and magnetic tunnel junction (MTJ) elements with semiconductor materials, new classes of magnetoelectronic devices such as magnetic tunnel transistor (MTT) have gained intensive interest<sup>3–8</sup> because they can be used as a source of highly spin-polarized electron current to inject into semiconductors. Until now, most of measurements on this class of device were performed at temperatures ( $T$ ) higher than 80 K. However, the knowledge of the behavior of MTT at low temperature (LT) is still deficient. In this work, we have performed the measurement of MTT on Si at LT ( $< 25\text{K}$ ). A new phenomenon of interfacial trapping of hot electron has been evidenced at the Cu/Si interface. At low temperature, the collected hot electron current in Si is reduced several tens of times, and the magnetocurrent (MC) ratio is decreased by half. A simple analytic model considering the interfacial electron trapping and releasing is proposed to explain the experimental results.

We have fabricated MTT with a spin-valve (SV) structure for the base and a MgO tunneling barrier for the emitter on Si substrate by magnetron sputtering. First, two samples with 10 nm Cu/4 nm NiFe/3.5 nm Cu/4 nm Co/2.7 nm MgO/20 nm Cu multilayers have been grown on n-doped and undoped Si, respectively. The use of a 10 nm Cu in direct contact with Si instead of NiFe is to avoid the formation of a magnetically dead silicide layer<sup>9</sup> and to benefit the good Schottky barrier (SB) property of Cu/Si and large hot electron attenuation length of copper.<sup>10</sup> A third reference sample without SV structure with 10 nm Cu/2.7 nm MgO/20 nm Cu multilayers has been grown on n-Si. The n-doped Si substrate has the doping concentration ( $N_D$ ) about  $3 \times 10^{14}\text{cm}^{-3}$  and the resistivity ( $\rho$ ) is about 1–10  $\Omega\text{cm}$ . The undoped Si has  $\rho \geq 5\text{k}\Omega\text{cm}$  and the unintentional  $N_D \approx 1 \times 10^{12}\text{cm}^{-3}$ . The samples are then processed with UV lithography

procedure to define the junction and fabricate the electrode contacts on the top Cu (emitter), the bottom metal (base), and Si substrate (collector). The top view of MTT device after lithography is shown in Fig. 1(a).

As schematically shown in Fig. 1(b) for the device band diagram, we apply an emitter bias ( $V_e$ ) across the MgO barrier, while we measure the collector current ( $I_c$ ) for the electrons injected into the Si substrate with different configuration of magnetizations of the SV base with an in-plane (IP) magnetic field ( $H$ ). When  $|V_e| > 0.6\text{V}$ ,  $I_c$  increases rapidly [Figs. 1(c) and 1(e)]. This threshold bias corresponds to the SBH of Cu on Si ( $\sim 0.6\text{eV}$ ).<sup>10,11</sup> Due to the larger mean free path ( $\lambda$ ) when hot electrons pass through the metallic SV base with a parallel (P) state than with an antiparallel (AP) state,  $I_c$  is larger in P state than in AP state. The MC ratio is defined as  $MC = (I_{c,P} - I_{c,AP})/I_{c,AP}$ , where  $I_{c,P}$  and  $I_{c,AP}$  are the collector currents for P and AP alignments, respectively. The maximum of MC ratio is found to be 1700% at 25 K for n-Si sample [inset of Fig. 1(d)] and 2750% at 29 K for undoped-Si sample [inset of Fig. 1(f)], respectively. If we assume that the effective transmission polarizations ( $P_E$ ) of two ferromagnetic (FM) layers are identical,  $P_E$  can be estimated with  $P_E = [MC/(2 + MC)]^{1/2}$  to be 0.97 with the 2750% MC ratio, which indicates a very large polarization efficiency through the high quality SV structure. The higher MC ratio for undoped-Si sample compared to n-Si sample is probably due to the better energy filtering for the SB of Cu on undoped Si with broader depletion layer. As shown in Figs. 1(d) and 1(f), the MC ratio decreases with the increase of  $V_e$ . This is caused by the spin-dependent inelastic scattering in the FM base layers. As a consequence, the electron energy distribution at the base/collector interface is broader for AP than for P state. Therefore, the MC ratio is largest at the onset of hot electron collection, i.e., when  $V_e$  is only slightly higher than the collector SBH. With increase of  $V_e$ , the SB does not efficiently block the hot electrons after inelastic scattering in AP state, so MC values are reduced.<sup>7</sup>

The most striking behavior we have observed takes place at LT ( $< 25\text{K}$ ). Figs. 1(c) and 1(e) show  $I_c$  vs.  $V_e$  curves at temperature range from 12 K to 35 K for MTTs on n-Si and undoped Si, respectively. For n-Si,  $I_{c,P}$  and  $I_{c,AP}$

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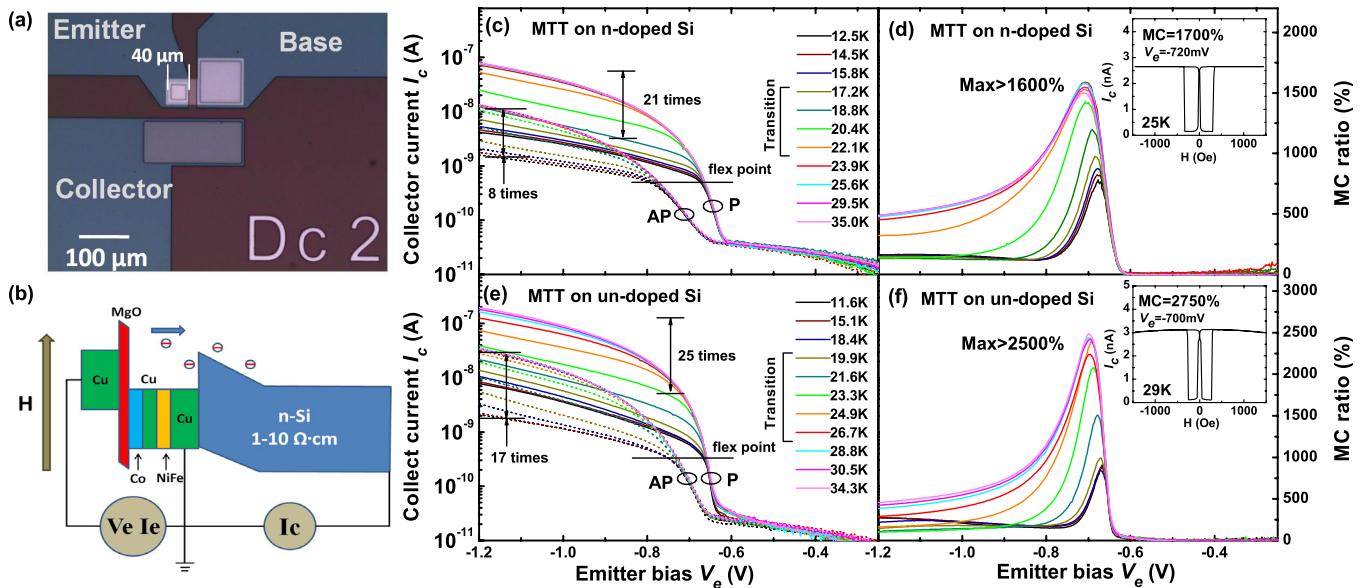


FIG. 1. (a) Top view of MTT device after lithography. (b) Schematic band diagram of MTT on n-Si for hot electron injection. Emitter bias dependent hot electron collector current in (c) n-doped Si and (e) undoped Si with base FM layers in P state (solid lines) and AP state (dashed lines) at low temperature from 12 K to 35 K. Emitter bias dependent MC ratio for MTT on (d) n-doped Si and (f) undoped Si from 12 K to 35 K. The maximum of MC ratio is 1700% for n-Si sample [inset of (d)] and 2750% for undoped-Si sample [inset of (f)].

simultaneously dramatically decrease with a transition temperature ( $T_{tran}$ ) window from 24 K to 16 K. The intensity of  $I_C$  at  $V_e = -1.2$  V decreases 21 times for P state and 8 times for AP state. The MC ratio also decreases with temperature. As shown in Fig. 1(d), the peak of the bias dependent MC becomes quite narrow, and the maximum decreases from 1600% at 25 K to 750% at 15 K. The sample on undoped Si shows a similar behavior.  $I_{C,P}$  decreases 25 times and  $I_{C,AP}$  decreases 17 times at  $V_e = -1.2$  V with  $T_{tran}$  window from 27 K to 19 K. The maximum of MC ratio decreases from 2500% at 29 K to 800% at 17 K. If we carefully analyze the  $I_C$  change at different temperatures for P and AP states, we can find that the decrease of  $I_C$  becomes significant when it reaches a critical value of intensity inducing a flex point in the emitter bias dependent  $I_C$  curves at LT, which is almost the same about 0.5 nA in P and AP states for both samples. This flex point provides an important clue that the decrease of  $I_C$  is sensitive to the intensity of injected hot electrons.

Another specific behavior at LT is observed when  $I_C$  is measured as a function of magnetic field. When  $T > T_{tran}$ ,  $I_{C,P}$  has little variation with  $H$  [inset of Fig. 1(d)]. However, below  $T_{tran}$ ,  $I_{C,P}$  changes with the applied field and also depends on  $V_e$ . Fig. 2 shows the bias dependent  $I_C$  with different magnetic field at 12 K for n-Si MTT, also the corresponding  $I_C$  vs.  $H$  curves at two different  $V_e$  around the flex point. At low bias of  $-650$  mV before the flex point, the variation of  $I_{C,P}$  is relatively small [Fig. 2(b)]. However, at the flex point of  $-680$  mV, the variation becomes evident to be about 25% change for  $I_{C,P}$  with 1500 Oe field [Fig. 2(c)], and the curvature of IH curve in P state is symmetric for both positive and negative field. The sample on undoped Si shows a similar behavior of curvature of IH curve in P state around the flex point at LT (not shown).

It is noted here that due to the IP magnetization of FM layers, we have to apply an IP field to get the P and AP configurations. However, when the hot electrons travel vertically

through the magnetic field, the spurious Hall signals due to Lorentz force will make the IH curve become complicate, especially for high  $V_e$  condition. Therefore, to simplify the geometry and explore the origin of the hot electron current suppression, we choose to study a non-magnetic tunnel junction (NM-TJ) injector (Cu/MgO/Cu) on n-Si with an out-of-plane (OP) magnetic field. Fig. 3(a) shows the bias dependent  $I_C$  at different temperatures without field for the non-magnetic sample. Without field, this sample shows the same behavior as samples studied before that the collector current reduces quickly when  $T < 25$  K and a flex point exists with  $I_C \approx 0.3$  nA at 13.4 K. Fig. 3(c) shows the bias dependent  $I_C$  with different OP field at 13.4 K.  $I_{C,P}$  reduces with the magnetic field, and it exhibits a symmetric feature for positive and negative field even with large  $V_e$ , which is different from the above MTT samples measured with IP field. However,

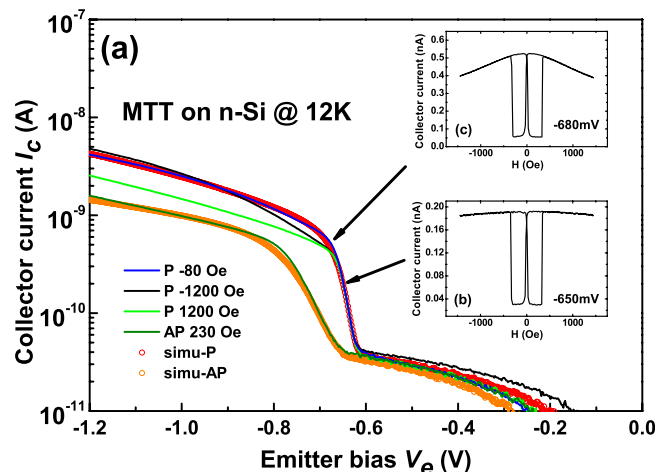


FIG. 2. (a)  $I_C$  vs.  $V_e$  curves for MTT on n-Si with different IP magnetic field at 12 K. The curves in P ( $-80$  Oe) and AP (230 Oe) are fitted with the interfacial trapping model using the same parameters for  $A = 0.953$  and  $B = 0.924$  nA.  $I_C$  vs.  $H$  curves at (b)  $V_e = -650$  mV and (c)  $V_e = -680$  mV.

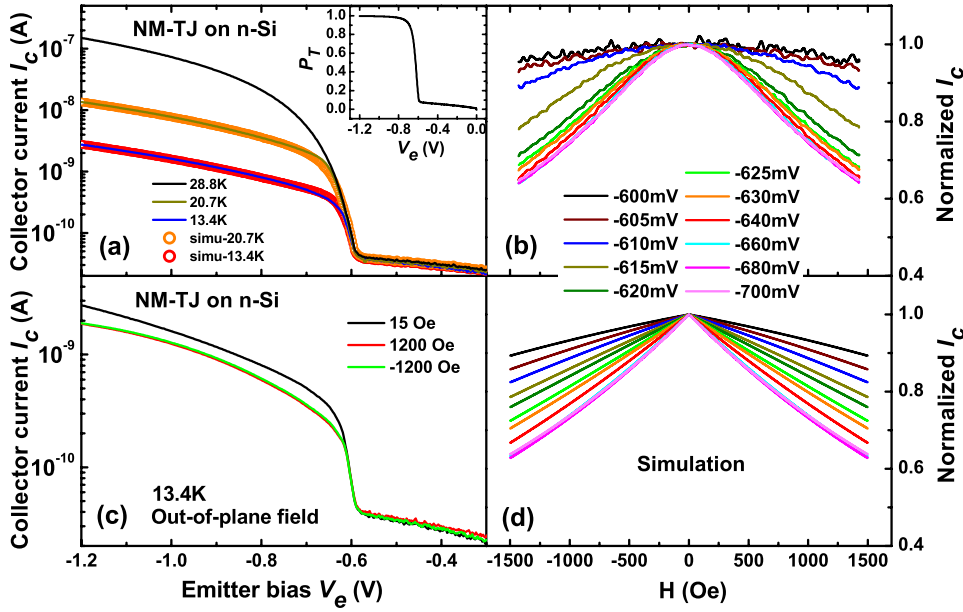


FIG. 3. (a)  $I_c$  vs.  $V_e$  curves for non-magnetic injector on n-Si at different temperatures. The curves at 13.4 K and 20.7 K are fitted by the interfacial trapping model. Inset: emitter bias dependent occupation probability ( $P_T$ ) at 13.4 K. (b) Normalized  $I_c$  vs. OP magnetic field with different  $V_e$  at 13.4 K. (c)  $I_c$  vs.  $V_e$  curves with different OP field at 13.4 K. (d) Simulated normalized  $I_c$  vs.  $H$  curves with different  $V_e$  at 13.4 K. The fitting parameters are  $A = 0.985$ ,  $B = 0.49$  nA, and  $\gamma = 4 \times 10^{-4}$ .

the IH curve shows the same curvature feature around the flex point. Fig. 3(b) shows the IH curves with different  $V_e$  around the flex point at 13.4 K, which has been normalized with  $I_c$  at zero field. The curvature becomes important with the increase of  $V_e$  and saturates with bias above  $-640$  mV, which value is correlated to the flex point. Based on the results of the three samples, it seems that the curvature behavior is related to the Cu/Si Schottky barrier and has a relationship with the hot electron current reduction around the flex point. A possible mechanism responsible for the limitation of hot electron current could be the trapping of hot electron at the Cu/Si interface which happens when  $T < 25$  K. The trapped electrons at the Cu/Si interface modify the interfacial electronic potential and make a backscattering to the injected hot electrons and therefore decrease the collector current. A certain amount of injected hot electrons is needed to fully fill the interface traps which can explain the same flex point current intensity for P and AP states. The magnetic field can increase the trapping electron binding energy<sup>12,13</sup> and enhance the occupation probability of traps, so it results in the curvature behavior in the IH curves.

To confirm this interpretation, we propose a simple analytic model considering the interfacial electron trapping and releasing to fit the experimental  $I_c$  vs.  $V_e$  and  $I_c$  vs.  $H$  curves. To simulate the current suppression due to interface trapped hot electrons, we first model the occupation probability  $P_T$  in the traps by queuing theory<sup>14</sup> as below

$$P_T = \frac{\tau_t}{\frac{\tau_i}{\alpha} + \tau_t}, \quad (1)$$

where  $\tau_t = C e^{\frac{E_b}{k_B T}}$  is the trapping time scale of electrons with Arrhenius distribution.  $\tau_i$  is the mean time between incident electrons which is inversely proportional to the injected hot electron current  $I_0$  and  $\alpha$  is the capture probability. Due to the occupation of traps, the trapped electrons will exert an electrostatic repulse force to the injected hot electrons and enhance the backscattering effect. Therefore the collected current suppression can be expressed by the equation as below

$$I_c = I_0(1 - \eta N_T P_T), \quad (2)$$

where  $N_T$  is the density of interface traps. The injected current  $I_0$  will be suppressed proportionally to the density of occupied traps  $N_T P_T$  with a coefficient  $\eta$ . Now let us inject Eq. (1) into Eq. (2); then, we get as below

$$I_c = I_0 \left( 1 - \eta N_T \frac{C e^{\frac{E_b}{k_B T}}}{\frac{1.6e^{-10}/I_0}{\alpha} + C e^{\frac{E_b}{k_B T}}} \right) = I_0 \left( 1 - \frac{A I_0}{I_0 + B} \right), \quad (3)$$

where  $A = \eta N_T$  and  $B = \frac{1.6e^{-10}}{C \alpha e^{\frac{E_b}{k_B T}}}$ . In experiment, we can use the bias dependent  $I_c$  above  $T_{tran}$  as  $I_0$  to fit the curves below  $T_{tran}$  to obtain the parameters of  $A$  and  $B$ . As shown in Fig. 3(a), we have fitted the curves at 13.4 K and 20.7 K using the data at 28.8 K as  $I_0$ . The relative good fitting with only two parameters  $A$  and  $B$  shows that our interfacial trapping model is reasonable. For 13.4 K, the fitted parameter values are  $A = 0.985$  and  $B = 0.49$  nA. The trapping probability can then be extracted from  $P_T = \frac{\tau_t}{\frac{\tau_i}{\alpha} + \tau_t} = \frac{I_0}{I_0 + B}$ . As shown in the inset of Fig. 3(a),  $P_T$  increases rapidly when the injected hot electron energy is above the SBH, and this results in the flex point in the  $I_c$  vs.  $V_e$  curves.

With the fitted  $A$  and  $B$ , we can further model the curvature behavior in the IH curves at LT as shown in Fig. 3(b). Here the binding energy  $E_b$  for the trapped electron is assumed to increase proportionally with the increase of the magnetic field  $E_b(H) = E_{b0}(1 + \gamma H)$  with a coefficient  $\gamma$ , since the magnetic field can cause the shrinkage of the trapped electron wave functions.<sup>12,13</sup> From the transition temperature range (17–22 K), the binding energy  $E_{b0}$  can be estimated to be 1.7 meV ( $k_B T_{tran}$ ). With the experimental results of  $I_c$  at 28.8 K as  $I_0$ , we can fairly well reproduce the curvature feature of IH curves when choosing  $\gamma = 4 \times 10^{-4}$  [Fig. 3(d)], which means that  $E_b$  increases to 2.7 meV with a field of 1500 Oe. It is worth mentioning that our simulation can especially reproduce the saturated curvature feature when  $|V_e| > 640$  mV.

The influence of magnetic field on the binding energy has already been studied in the spin-singlet ground states of a negative donor ( $D^-$ ) ion in bulk Si and Si/SiO<sub>2</sub> quantum wells.<sup>13</sup> From the IH curvature feature and the found  $E_b$  about 1.7 meV, it is natural to correlate our finding to the formation of the  $D^-$  states which results in the collector current suppression at LT. However, this assumption cannot explain why the samples made on Si with different doping concentration show similar amplitude of reduction of  $I_c$  since the density of trapping center due to  $D^-$  states should be proportional to  $N_D$ . Another possible explanation to the trapping center is the defects or interface states<sup>15</sup> located at the Cu/Si interface due to the formation of a Cu-Si inter-diffusion silicide layer, as evidenced in Ref. 16. This assumption seems reasonable because it is valid for all samples studied here with the same Cu/Si interface. However, to definitively identify the origin of trapping center and extract their density, dynamic measurements of  $I_c$  around the flex point is necessary.

Our simulation shows that the flex point is directly related to the trapping occupation probability, which appears at identical injected hot electron intensity for P and AP states. However, the amplitude of reduction is 2–3 times higher in P than AP state, which results in the decrease of MC ratio at LT. In Fig. 2(a), we show the simulated bias dependent  $I_{c,P}$  and  $I_{c,AP}$  with the same  $A$  and  $B$  for n-Si sample at 12 K. The fairly good fitting means that the trapped electron scattering in our case is almost *spin-independent* due to the same fitting parameters for P and AP states. In fact, the different amplitude of suppression of  $I_c$  is due to the smaller injected hot electron current  $I_0$  in AP state.

In summary, we have evidenced a new interfacial trapping phenomenon for hot electron injection in silicon. At

low temperature ( $<25$  K), the trapped electrons at Cu/Si interface enhance the backscattering to injected hot electrons, which results in a large reduction of the collector current and a rapid decrease of the magnetocurrent ratio.

We thank Professor M. W. Wu for fruitful discussion. This work was supported by French ANR SpinPress project and region Lorraine.

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