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Tunnel barrier fabrication on Si and its impact on a spin transistor

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Abstract

The realization of many future spintronic devices requires efficient spin injection into semiconductor structures. Critical considerations include interfacial intermixing of the metallic components and oxygen with Si, and the conditions for Schottky barrier formation. Both impact the design of a silicon-based spin transistor, which tunnel-injects carriers from a ferromagnetic emitter into the Si base and then tunnel-collects them via a ferromagnetic collector. A discussion of the characteristics of this spin tunnel transistor will be presented, including its behavior and magnetic sensitivity.

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Following recent theoretical work [1–3], electrical spin injection from ferromagnetic metals into semiconductors has focused on using a spin selective contact (tunnel barriers, Schottky barriers, etc.) between the ferromagnetic metal and the semiconductor. This method has been experimentally verified on GaAs-based systems [4,5]. However, Si technology is the basis for over 90% of the semiconductor market. This motivated an investigation of the fabrication and properties of tunnel barriers on Si.

This work focused on transferring the existing technology of good spin tunnel barriers (Al_2O_3 and ZrO_2) onto Si. Both of these tunnel barriers have been shown to spin inject with TMRs greater than 50% for Al_2O_3 and 40% for ZrO_2 or Al_2O_3/ZrO_2 mixtures [6–8]. In particular, the methods of fabrication of Al_2O_3 on metals are very well known, and it is the usual choice for a spin tunnel barrier. However, it has been shown that the Al will diffuse into the Si to form a metal, AlSi [9,10], so ZrO_2 was also investigated because Zr is a heavier element than Al. (The solubility of Si in Al is 3%.) Previous work [9] examined the non-metal based tunnel barriers of Si_3N_4 and SiO_2. Si_3N_4 proved not to be a good spin tunnel barrier due to hopping conduction and SiO_2 was electrically unstable.

In the first part of this paper, the critical elements involved in fabricating good spin tunnel barriers on Si

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will be discussed, including general processing requirements. The second part examines the electrical and magnetic characteristics of a spin tunnel transistor, before concluding with a discussion of how the tunnel barrier fabrication affects its design.

From the problems encountered during the fabrication of magnetic tunnel junctions (MTJs), some of the critical elements in the formation of good spin tunnel barriers on Si become apparent. The first element of importance is intermixing at the interface. The second is the presence of amorphous Si at the interface. The third is the formation of a Schottky barrier. Each of these has a detrimental effect on the spin injection, but for different reasons.

The intermixing at the interface can be caused by diffusion of the metallic component of the tunnel barrier into the Si, diffusion of the Si into the metallic component, or diffusion of the oxygen into the Si. The mixing of the metallic component with the Si is a direct result of the deposition conditions and also of post-deposition annealing (a standard procedure to improve the oxygen distribution within the barrier). The general method for depositing tunnel barriers is to deposit the metallic component and then oxidize it. This allows the metal to diffuse into the Si. Furthermore, the energy with which metallic atoms impact the substrate in sputtering (the primary deposition method) allows them to displace Si atoms more readily, dispersing themselves inside the crystalline Si. Even if the atoms do not readily displace Si atoms on deposition, their increased energy allows them greater mobility in the time prior to oxidation. Overall, the intermixing at the interface can create a non-magnetic metal–semiconductor contact which will destroy any injected spin polarization, or it can change the potential barrier. Since theory [2] predicts that there is a specific range for the tunnel barrier resistance, this barrier modification may reduce the amount of spin injected.

In the second element, a layer of amorphous Si at the interface is due to either the process for removing the native oxide or the deposition of the tunnel barrier itself. The native oxide that is present on the Si surface (which forms after even a brief exposure to air) is very rough (a measured RMS roughness from AFM of 3 nm vs. 0.2 nm for a deposited tunnel barrier) in addition to being of non-uniform thickness and density. This renders the native oxide un-usable as a tunnel barrier, regardless of its electrical stability. Therefore, this native oxide must be removed, for which there are two common methods. In the first, a standard BHF dip will remove the oxide with minimal damage to the underlying Si. However, this process is done in air, so the sample must be cleaned and dried rapidly and then immediately loaded into a vacuum chamber to minimize its exposure to oxygen and prevent the formation of another native oxide layer. The second is ion etching of the surface. This process is done in situ, so there is a minimum of oxygen exposure. However, this process implants a small number of ions into the Si substrate, as well as energetically causing reorganization of the Si surface which can lead to the formation of an amorphous layer. This adds another barrier which may reduce the level of spin injection, as mentioned previously.

The third element, the formation of a Schottky barrier at the interface, originates from an inability of the tunnel barrier to support the difference in potentials between the Si and the metal on the other side of the tunnel barrier (normally a ferromagnetic metal). This has been explored theoretically [10], and it can be shown that the tunnel barrier would need to be at least 200 nm thick for typical doping levels in Si, in order to support the potential difference without any band bending. Albrecht and Smith [3] have shown theoretically that a thick Schottky barrier can be detrimental to spin injection. If the Schottky barrier is reduced by delta doping (for example), then it is possible to inject spins through it, as shown with Fe on GaAs [5].

Experimentally, evidence for the intermixing of metals and Si has been observed using elemental mapping in TEM with electron energy loss spectroscopy (EELS). Clear diffusion of both the Al and the O into the Si has been observed (Fig. 1), along with a commensurate increase in the layer of amorphous Si close to the interface. A simple solution to this problem will be suggested in Ref. [10]. However, even after removing the problem of intermixing, Schottky barriers still exist at the interface. This is shown in Fig. 2, when a 5 Å tunnel

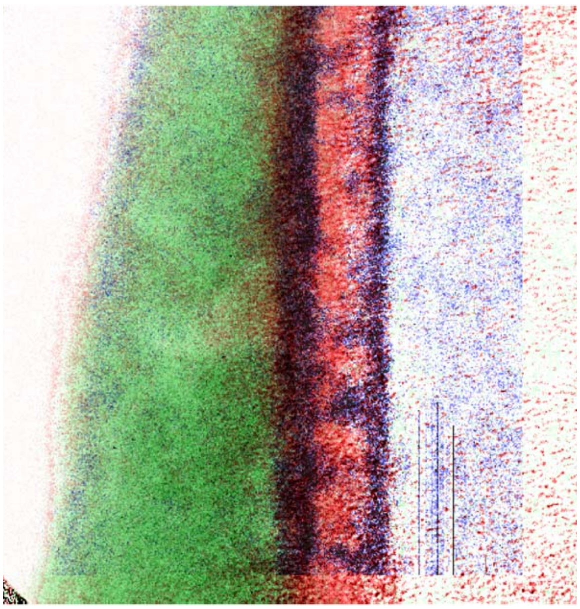

Fig. 1. Elemental map by EELS of Al_2O_3 onto Si. The green is for the Si, the red is for the Al, and the blue is for the oxygen.

barrier remains intact after 20 V are applied to it. Furthermore, the electrical characteristics are not tunnel-like, and do not vary with changes in thickness or area. An additional problem that needs to be characterized is the stability of the tunnel barriers. (The number of surface states that exist on a Si surface make instability a very real concern, particularly a long-term instability that would be detrimental for devices.)

Spin tunnel transistors have been fabricated and measured previously [9,11] using SiO_2 and Si_3N_4 tunnel barriers. While promising, the results showed that significant work is still needed, primarily in the areas of better magnetic materials and better tunnel barriers.

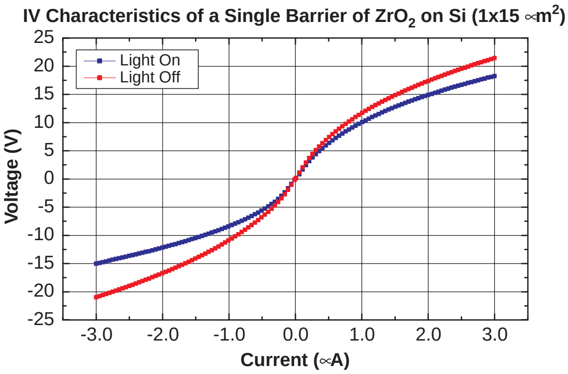

Fig. 2. Electrical characterization of a ZrO_X tunnel barrier.

Both of these concerns have been addressed in a second generation of these transistors. In these devices, tunnel barriers of Al_2O_3 and different magnetic materials of Co/Fe (on the emitter and base) and CoFe (on the collector) were used.

These transistors operate by tunnel injecting spin-polarized electrons from the ferromagnetic emitter into the Si base. These electrons then traverse the base under a combination of diffusion and drift, before being tunnel collected by the ferromagnetic collector. The base current and the collector–emitter voltage modify the collector current by controlling the total voltage drop across the tunnel barriers, the relative voltage drop across the emitter and collector barriers, and the rate of recombination in the Si. The application of a magnetic field modifies the operation by (1) changing the relative orientation of the collector and emitter to introduce a spin-selective tunneling collection probability, and (2) decreasing the electron mean free path in the Si by Lorentz magnetoresistance. The expected characteristics of this device are shown in Ref. [12].

The experimental results are discussed in detail in Ref. [13]. Unfortunately, due to the Si quality, their current gain did not improve as compared to their predecessor (with Si_3N_4 tunnel barriers). However, the different magnetic materials improved the magnetic sensitivity of the device from 3.3% to 13.4%—a factor of 4 (Fig. 3). Unfortunately, the two-terminal results confirm the existence of a Schottky barrier.

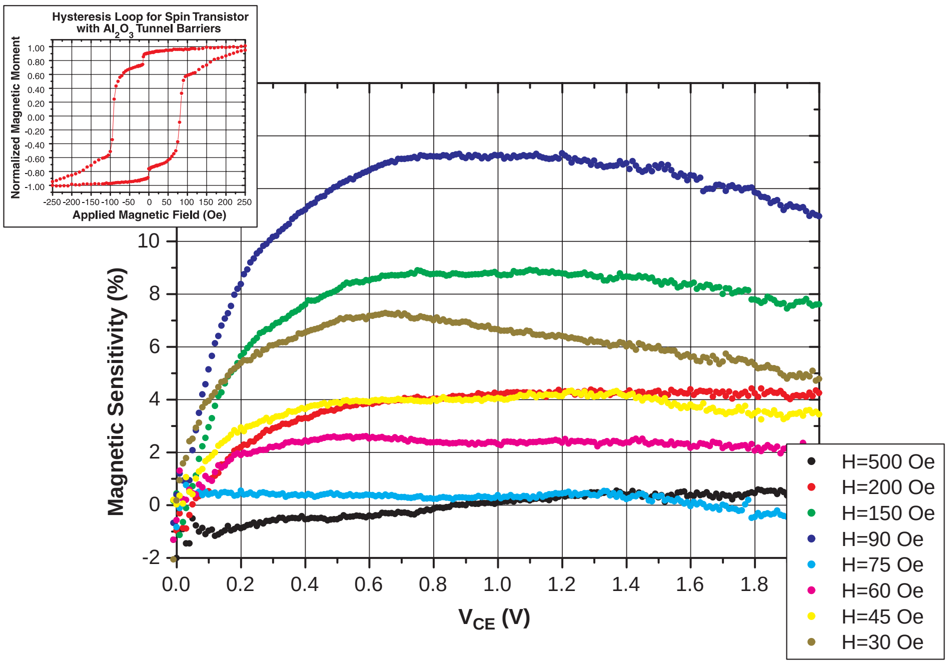

Fig. 3. Magnetic sensitivity of the spin transistor with Al_2O_3 tunnel barriers and $I_B = -0.2\,\mu A$.

Finally, for the design outlined in Ref. [11], there are two major requirements. The first is ion doping the top surface of the Si wafer to modify the Schottky barrier. The level of doping is a design parameter, since it will depend upon the choice of materials on either side of the tunnel barrier (which will influence the potential difference that the tunnel barrier must support). This must be accounted for in conjunction with the choice of tunnel barrier materials, since the resistance of the tunnel barrier must be in a specified range to enhance spin injection. The second major impact affects the deposition of the tunnel barriers. In order to achieve the best operating characteristics, the collector should be significantly larger than the emitter. The area should not be so large that pinholes or density fluctuations form in the tunnel barrier, nor should it be so small that reasonable current levels cannot be achieved. Furthermore, the shape of the contact areas must be optimized for single-domain and coherent switching of the magnetic materials.

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