Nanoelectronics with Spin

V. Sverdlov, J. Ghosh, A. Makarov, T. Windbacher and S. Selberherr
Institute for Microelectronics, TU Wien, Austria

The breath-taking increase in performance of nanoelectronic circuits has been continuously supported by the uninterrupted miniaturization of devices and interconnects. Among the most crucial technological changes lately adopted by the semiconductor industry is the introduction of a new type of multi-gate three-dimensional (3D) transistors [1]. This technology combined with strain techniques and high-k dielectrics/metal gates offers great performance and power saving advantages over the planar structures and allows continuing scaling down to 14nm feature size and beyond. In order to continue with scaling further, a new material with improved transport characteristics for the channel must be introduced [2]. Although single devices with gate length as short as a few nanometers have been demonstrated [3], fabrication, control, and integration costs combined with reliability issues will gradually bring conventional transistor scaling to an end. The principle of transistor operation is fundamentally based on the charge of an electron interacting with the gate voltage induced electrostatic field. Another intrinsic electron characteristic, the electron spin, attracts at present much attention as a possible candidate for complementing or even replacing the charge degree of freedom in future electronic devices. The electron spin state is characterized by two projections on an axis and could be potentially used in digital information processing. In addition, it takes an amazingly small amount of energy to invert the spin orientation. The key advantages of all spin-based computing as compared to a conventional processor with equivalent functions are zero static power, small device count, and low supply voltage, as listed in a recent review [4].

Silicon, the most important material of electronics, predominantly consists of nonmagnetic $_{28}$Si nuclei and is characterized by weak spin-orbit interaction. Because of these properties the electron spin lifetime in silicon is relatively long. This makes silicon a perfect candidate for spin-driven device applications. However, even a demonstration of basic elements necessary for spin-related applications, such as spin injection, detection, and propagation was missing until recently. The fundamental reason has been identified as an impedance mismatch problem [5]. Even though there is a large spin imbalance between the majority and minority spins in a metal ferromagnet, both channels with spin-up and spin-down are equally populated in a semiconductor due to the small density of states as compared to that for the minority spins in a ferromagnet. In other words, because of the large resistance of the semiconductor, the voltage applied to the contact between the ferromagnet and the semiconductor drops completely within the semiconductor, and the properties of the contact are dominated by the non-magnetic semiconductor, thus resulting in a current without spin polarization. A solution to overcome this problem is to use the hot electron injection [6]; however, the efficiency of spin injection and detection is low. Another solution to the impedance mismatch problem is the introduction of a potential barrier between a metal ferromagnet and a semiconductor [7]. In this case the influx of carriers from the ferromagnet into the semiconductor is reduced proportionally to the ration of the densities of states in a semiconductor and a ferromagnet. This guarantees the spin injection into the semiconductor. A successful experimental proof of spin injection at low temperature from an iron electrode through aluminium oxide [8] was demonstrated in 2007. At room temperature spin injection into n- and p-doped silicon was shown in 2009 [9]. The authors used heavily doped silicon samples to avoid an extended depletion layer causing large tunnel barriers. The problem of making good contacts with low resistance per area is critical for spin injection. Tunnel contacts made of a single layer graphene [10] have been shown to be close to optimal [11]. Electrical spin injection through silicon dioxide at temperatures as high as 500K has also been demonstrated [12].

Regardless of an ultimate success in demonstrating spin injection into silicon at room temperature, there are unsolved issues, which may compromise the present understanding of the spin injection process in general. One problem is a several orders of magnitude discrepancy between the signal measured in a scheme where the same ferromagnetic contact is used to inject and to measure the spin accumulation and its theoretical value [11]. Similar observations were also made for germanium [13] as well as for other semiconductors [14]. These discrepancies are heavily debated [15], [16], [17] and more research is needed to resolve the controversies. The excess spin is not a conserved quantity: While diffusing, it gradually relaxes to its equilibrium value which