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Very Low Electron Density in Undoped Enhancement-Mode Si/SiGe Two-Dimensional Electron Gases with Thin SiGe Cap Layers

Chiao-Ti Huang, Jiun-Yun Li and James C. Sturm

Princeton University, Department of Electrical Engineering and Princeton Institute for the Science and Technology of Materials, Princeton, New Jersey 08544

Single-electron quantum dot (QD) devices fabricated from Si/SiGe two dimension electron gases (2DEGs) are attractive due to the weak spin coupling and resulting long relaxation time in silicon [1]. Recently, a metal-oxide-semiconductor (MOS) gated undoped enhancement-mode Si/SiGe heterostructure using a thick SiGe (150 nm) cap layer was demonstrated as an approach to realize a single-electron QD in silicon due to its capability to tune the 2D electron density (n_{2D}) in a strained Si 2DEG (Fig. 1) to a very low level, which in turn facilitates the process to isolate a single electron [2]. The thick SiGe cap layer separates the 2DEG from the surface, leading to high mobility (μ). However, to create a very small 2DEG to hold one electron requires a much thinner SiGe cap layer (< 60 nm) for sharp lateral confinement. In this study, we demonstrate gated undoped thin-SiGe-cap (27-55 nm) Si/SiGe 2DEGs with very low n_{2D} and high μ.

The undoped Si/SiGe heterostructures were all grown on graded buffer layers by rapid thermal chemical vapor deposition (RTCVD) at 575-625 °C (Fig. 1). The enhancement-mode Si/SiGe 2DEGs were then fabricated on the heterostructures as shown in Fig. 1. A typical gate voltage (V_G) dependence of the 2D electron density (n_{2D}) was shown in Fig. 2. When V_G is above the threshold voltage, electrons are capacitively induced in the strained Si quantum well, leading to the onset of channel conductance (Fig. 2, inset). The slope of n_{2D} v.s. V_G describes the experimental capacitance, near that expected from a parallel capacitance plate model.

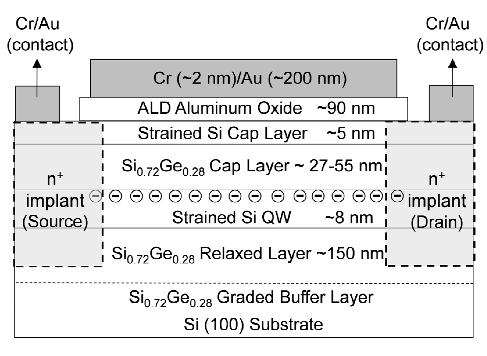

Fig. 1 The schematic of an undoped enhancement-mode Si/SiGe Heterostructure. A 2DEG is induced in the strained Si quantum well (QW) by a positive gate voltage.

To understand the limiting factors in transport, mobility at 4K was measured as a function of n_{2D} (Fig. 3a). The highest μ and lowest n_{2D} of samples with a 55-nm (circles) and a 27-nm (triangles) SiGe cap are ~400,000 cm^2/Vs and ~200,000 cm^2/Vs, and 4.9×10^{10} cm^{-2} and 1.1×10^{11} cm^{-2}, respectively. Below a critical electron density, the 2DEGs do not conduct at low temperature (i.e. they act as an insulator). This is fundamentally caused by potential fluctuations and by charges at scattering sites which localize electrons at low density. With such thin SiGe caps, these lowest densities before the metal-insulator transition (MIT) are 2-5× lower than previous results [3, 4], indicating very high sample quality with few potential fluctuations.

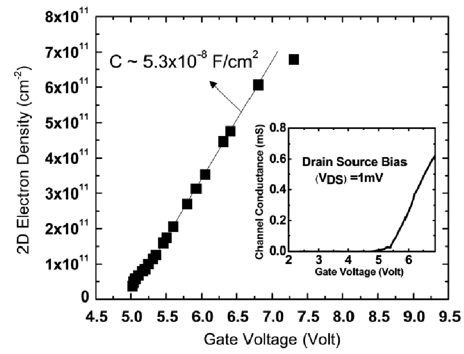

Fig. 2 The typical linear V_G dependence of n_{2D}. The inset shows the onset of channel conductance. (Temperature: 4K)

Models for mobility limits by (i) background impurity scattering, (ii) scattering by remote charges at the aluminum oxide/Si interface, and (iii) Si/SiGe interface roughness scattering, and their combination are also plotted in Fig. 3a [5]. Over a wide range of densities, the dominant scattering was scattering by remote charges ($\mu\sim n_{2D}^{1.5}$); the scattering by background impurity with density ($N_B\sim$ 4×10^{14} cm^{-3}) measured by secondary ion mass spectroscopy (SIMS) was not significant. At high density, interface roughness scattering may account for the saturation of the mobility. At low density regime, a sharp decrease of μ was observed in the sample with a 27-nm SiGe cap. This drop was modeled by MIT theory [6], assuming the source of fluctuations was charges of the aluminum oxide/Si interface (Fig. 3b).

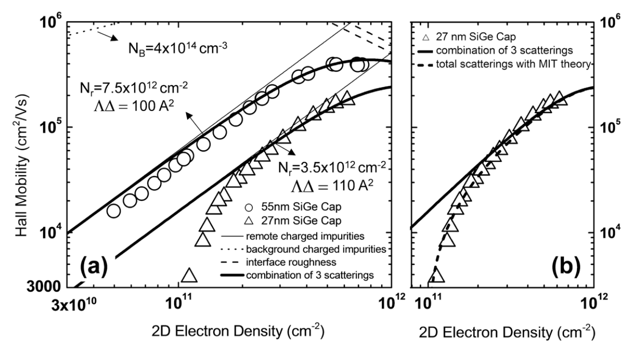

Fig. 3 (a) The n_{2D} dependence of μ at 4K and theoretical fitting based on various scattering mechanisms. N_r refers to remote impurity density and ΛΔ to the product of characteristic length and surface roughness. (b) A sharp decrease of μ described by the MIT model is added to the model of Fig. 3a.

In summary, undoped enhancement-mode Si/SiGe 2DEGs with thin SiGe caps were fabricated. The lowest electron densities before MIT are 2-5× lower than previous results with the similar SiGe cap thickness. A clear metal-insulator transition related to potential fluctuation caused by remote charges was observed at the low density regime.

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