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

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We report the lowest electron density (4.9×10^{10} cm^{-2} and 1.1×10^{11} cm^{-2}) and high mobility (~400,000 cm^2/Vs and ~200,000 cm^2/Vs) of undoped enhancement-mode Si/SiGe two-dimensional electron gases comparing to samples previously reported with similar thin SiGe cap thickness (55nm and 27nm). The dominant scattering mechanism over a wide range of two-dimensional electron density in both samples is the scattering from remote charges at oxide/silicon interface. In addition, a clear metal-insulator transition is observed in the sample with a 27-nm SiGe cap.

Introduction

Single-electron quantum dot (QD) devices fabricated from Si/SiGe two-dimensional electron gases (2DEGs) are attractive due to the weak spin coupling in silicon and resulting long relaxation time (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 a promising 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). In this case, the thick SiGe cap layer separates the 2DEG from the surface, leading to high mobility (μ).

To pattern an undoped 2DEG, fine metal gates are deposited on the surface of 2DEG to deplete 2D electrons induced by a universal gate. Therefore, to create a very small 2DEG to hold one electron, a much thinner SiGe cap layer (< 60 nm) is preferred due to sharp lateral confinement of electrons. In this study, we demonstrate gated undoped thin-SiGe-cap (27-55 nm) Si/SiGe 2DEGs with very low 2D electron density and high mobility.

Epitaxy Growth of Undoped Si/SiGe 2DEG and Fabrication

The undoped Si/SiGe 2DEGs used in this study were all grown on $Si_{0.72}Ge_{0.28}$ graded buffer substrates by rapid thermal chemical vapor deposition (RTCVD). A 150-nm SiGe buffer layer was first grown at 575 ^oC followed by the growth of a 8-nm strained silicon quantum well (QW) at 575 ^oC. Subsequently, a SiGe cap layer with varied thickness were then grown at 575 ^oC to see how the distance between the strained silicon QW (i.e.

2DEGs) and the surface affects the property of electron transport. Finally, a thin strained silicon layer (~ 4nm) was capped at 575 ^{o}C.

To study the electron transport at low temperature, an enhancement-mode Hall-bar device is subsequently fabricated and used to measure mobility and 2D electron density at liquid helium temperature (4.2 K). First, a 200-nm silicon dioxide layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the as-grown structure as an implant mask. The designated regions for Ohmic contacts were then defined by photolithography and wet etching of silicon dioxide. A 3-step phosphorus implantation was conducted to assure the implanted species were deep enough to form contacts from the surface to the strained Si QW. Samples were then annealed at 550-700 ^{o}C for 1 hour to activate the implanted phosphorus. Next, a 90-nm aluminum oxide was deposited by atomic layer deposition (ALD) at 300 ^{o}C as a gate insulator. Parts of n^+ implanted regions were exposed by photolithography and wet etching of the aluminum oxide for metal deposition for contacts. After another photolithography, a Hall-bar-shape metal gate was finally formed by evaporating 2-nm chrome and 200-nm gold layer with metal deposition on the exposed n^+ contact regions. We note that the metal gate must overlap with the n^+ contact regions to keep the continuity of conduction from the contacts to the 2DEG (Fig. 1).

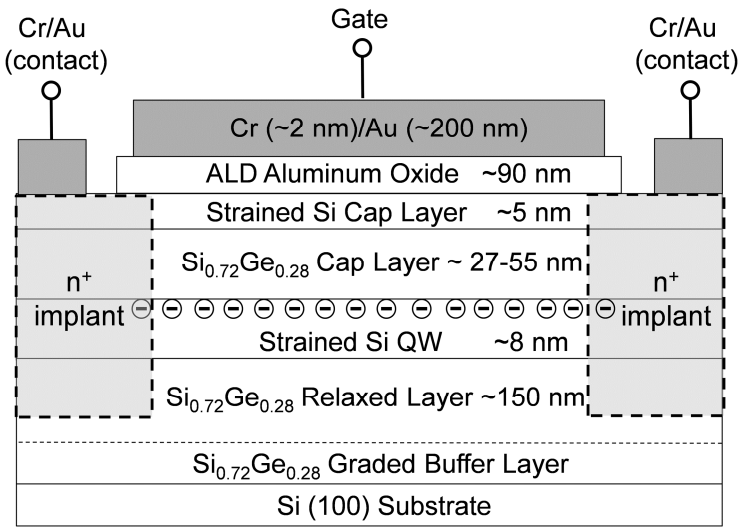

Figure 1. The schematic of an undoped enhancement-mode Si/SiGe heterostructure. A 2DEG is induced in the strained Si quantum well (QW) by a positive gate voltage.

Results and Discussions

When gate voltage (V_G) is above the threshold voltage, electrons are capacitively induced in the strained Si QW to form a 2DEG, leading to the onset of channel conductance (Fig. 2, inset). A typical gate voltage (V_G) dependence of the 2D electron density (n_{2D}) was thus obtained (Fig. 2). The slope of n_{2D} v.s. V_G describes the experimental capacitance (5.3×10^{-8} F/cm^2), near the theoretical capacitance calculated from a parallel capacitance plate model (6.1×10^{-8} F/cm^2).

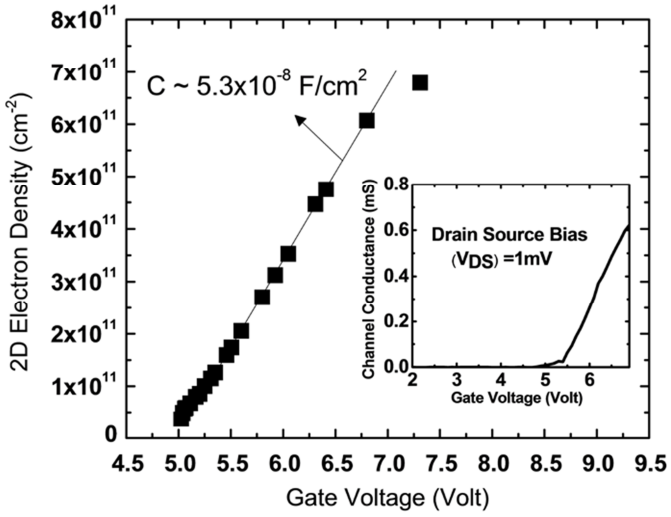

Figure 2. The typical linear V_G dependence of n_{2D}. The inset shows the onset of channel conductance. (Temperature: 4.2 K)

Low Electron Density of Undoped Enhancement-mode 2DEGs

To understand the limiting factors in electron transport, mobility at 4.2 K was measured as a function of n_{2D} (Fig. 3a) with a standard low-frequency lock-in technique. 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, such as charges at scattering sites, which localize electrons at low density (3, 4). With such thin SiGe caps, these lowest densities before the metal-insulator transition (MIT) are 2-5 times lower than previous results (5, 6) with similar SiGe cap thickness, indicating very high sample quality with few potential fluctuations.

Scattering Mechanisms of Electron Mobility

The possible scattering mechanisms (7) limit the electron mobility at 4.2K in our samples could be (i) background impurity scattering:

$$\mu_{bs} = \frac{g_v^{3/2} g_s^{3/2} e n_{2D}^{1/2}}{4\pi^{1/2}\hbar N_b} \qquad [1]$$

where g_v and g_s are valley degeneracy and spin degeneracy, respectively. N_b is the density of background impurity while μ_{bs} is the mobility limited by background impurity scattering.

(ii) the scattering from remote charges at the aluminum oxide/Si interface,

$$\mu_{rs} = \frac{16\pi^{1/2} g_v^{1/2} g_s^{1/2} e n_{2D}^{3/2} s^3}{\hbar N_r} \quad [2]$$

where s is the SiGe cap thickness. N_r is the 2D density of remote charges, and μ_{rs} is the mobility limited by the scattering from remote charges.

and (iii) Si/SiGe interface roughness scattering,

$$\mu_{irs} = \frac{e^5 g_v^3 g_s^3}{192\pi^4 \hbar (\varepsilon\varepsilon_0)^2 (\partial V/\partial z)^2 (\Lambda\Delta)^2 n_{2D}} \quad [3]$$

where Λ and Δ are characteristic length of the interface roughness and rms roughness, respectively. $\partial V/\partial z$ is a perturbation factor and μ_{irs} is the mobility limited by interface roughness scattering.

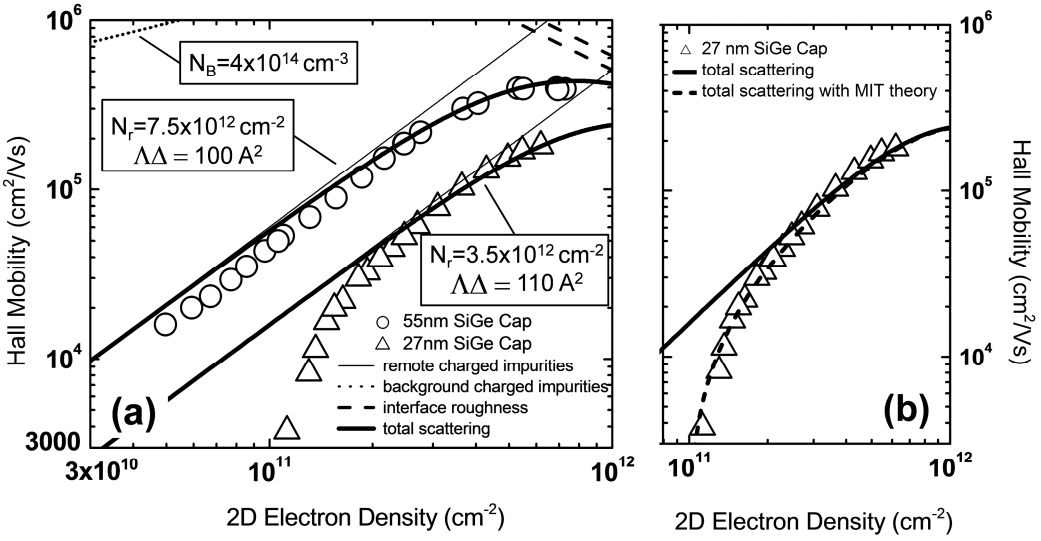

Fig. 3 (a) The n_{2D} dependence of μ at 4.2 K and theoretical fittings based on various scattering mechanisms with fitting parameters. N_r refers to 2D remote impurity density and ΛΔ to the product of characteristic length and surface roughness. (b) A sharp decrease of μ described by the MIT model is added to the model of Fig. 3a.

The theoretical model curves for mobility limits by these three scattering mechanisms fit to our data and total scattering are plotted in Fig. 3a. Over a wide range of 2D electron density, the dominant scattering mechanism was the scattering from remote charges ($\mu \sim n_{2D}^{1.5}$). The density of remote charges (N_r) chosen here are 7.5×10^{12} cm^{-2} and 3.5×10^{12} cm^{-2} for the samples with a 55-nm and a 27-nm SiGe cap respectively; the scattering by background impurities with density, $N_b \sim 4\times10^{14}$ cm^{-3}, measured by secondary ion mass spectroscopy (SIMS), was not significant. In addition, at high density, interface

roughness scattering may account for the saturation of the mobility. The product of the characteristic length of the interface roughness and rms roughness are 100 A^2 and 110A^2 for the samples with a 55-nm and a 27-nm SiGe cap, respectively.

Observation of Metal-Insulator-Transition in the sample with a 27-nm SiGe Cap

At low density regime, a sharp decrease of μ was observed in the sample with a 27-nm SiGe cap. This drop can be modeled by a MIT theory, assuming the source of fluctuations was charges at the aluminum oxide/Si interface (Fig. 3b). The model (8) used here includes a parameter A:

$$A = \frac{N_r}{16\pi {n_{2D}}^2 s^2}, if \;\; 4k_F s >> 1 \qquad [4]$$

where s is the SiGe cap thickness, N_r is the 2D density of remote charges and k_F is the Fermi wave number. Therefore, the mobility limited by the scattering of remote charges can be modified as

$$\mu_{rs}(n_{2D}) = \mu_{rs0}(n_{2D})(1-A) \qquad [5]$$

In high density regime, A is much smaller than 1, meaning that μ_{rs} is close to $\mu_{rs0.}$ The mobility is not degraded because the electron density is high enough to screen the influence of potential fluctuation from remote charges. However, once 2D density decreases (given a fixed N_r and s) and the parameter A approaches 1, μ_{rs} decreases sharply. The original model of the scattering from remote charges is no longer applicable. When A is 1, where the n_{2D} is defined as the critical electron density, the mobility drops to zero. The metal-insulator transition occurs at this point.

The sharp decrease of μ in the sample with 27nm SiGe cap is well modeled by the MIT theory, which indicates that the remote charges at the aluminum oxide/silicon interface, have a strong influence on the sample with such a thin cap layer. However, no similar phenomenon was observed in the sample with a 55-nm SiGe cap. Further investigation is needed to figure out if factors other than remote charges dominate its MIT.

Summary

In summary, undoped enhancement-mode Si/SiGe 2DEGs with thin SiGe caps were fabricated. The lowest electron densities before MIT are 2-5 times lower than previous results with a similar SiGe cap thickness. The dominant scattering mechanism over a wide range of density is the scattering from remote charges. At high density, the Si/SiGe interface roughness scattering may account for the saturation of mobility. The background impurity scattering is negligible in both samples. A clear metal-insulator transition related to potential fluctuation caused by remote charges was observed at the low density regime of the sample with 27nm SiGe cap.

Acknowledgments

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