Extremely Low Electron Density in a Modulation-Doped Si/SiGe Two-Dimensional Electron Gases by Effective Schottky Gating

J. Y. Li[a], C. T. Huang[a], L. P. Rokhinson[b], and J. C. Sturm[a]

[a] Department of Electrical Engineering and Princeton Institute for the Science and Technology of Materials, Princeton University, Princeton, New Jersey 08544, USA
[b] Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA

We reported an extremely low electron density (8.3×10^{10} cm^{-2}) of a modulation-doped Si/SiGe two-dimensional electron gas by Schottky gating. Eeffective Schottky gating with extremely low gate leakage current was enabled by low-temperature chemical vapor deposition epitaxial growth to suppress the surface segregation of phosphorus. Furthermore, an extremely high electron mobility of ~ 504,000 cm^2/V-s at 0.3 K was also reported.

Introduction

Silicon quantum dots (QDs) fabricated from a Si/SiGe two-dimensional electron gas (2DEG) are very promising for the realization of solid-state quantum computation (1). A 2DEG with a low electron density of is critical to isolate a single electron in a QD. However, due to the potential fluctuations induced by the remote dopants (2), it is difficult to reach a very low electron density in Si-based modulation-doped 2DEGs. In this work, we demonstrate an extremely low electron density of modulation-doped Si/SiGe 2DEG by Schottky gating. The gate leakage current was significantly reduced by low-temperature epitaxial growth to suppress phosphorus surface segregation. Moreover, we reported an very high electron mobility of ungated Si/SiGe 2DEGs.

Epitaxial Growth of Modulation-Doped Si/SiGe 2DEGs

To create a 2DEG in a Si/SiGe heterostructures, we used rapid thermal chemical vapor deposition (RTCVD) to grow epitaxial layers on polished $Si_{0.7}Ge_{0.3}$ graded buffer layers grown on Si (100) substrates. After ex-situ wet cleaning and in-situ hydrogen baking at 850 ^oC, a 150-nm $Si_{0.7}Ge_{0.3}$ buffer layer was grown followed by a 12-nm strained Si layer, where the 2DEG will reside. A setback $Si_{0.7}Ge_{0.3}$ layer of 10 ~ 60 nm was then grown to separate the 2DEG layer from a 10-nm phosphorus doped $Si_{0.7}Ge_{0.3}$ electron supply layer. Then a $Si_{0.7}Ge_{0.3}$ cap layer of 30 ~ 50 nm was grown at low temperature to suppress phosphorus segregation (3) to reduce the gate leakage current, followed by a thin Si cap layer of 4 nm (Fig. 1). The SiGe buffer, setback, and doped layers were grown at 575 ^oC, the SiGe cap layers was grown at 525 ^oC, and the Si layer was grown at 625 ^oC.

After epitaxial growth, Hall bars were defined by dry etching, and Au (1% Sb) was deposited and annealed at 450 ^oC to form ohmic contacts. For gated samples, Pd was thermally evaporated onto the surface of 2DEG samples. Electrical transport measurements were done at 4K and 0.3K to characterize the electron density and mobility.

For a sample with a setback layer of 10 nm and a cap layer of 30 nm, Shubnikov-de Haas oscillations showed spin splitting at 0.8 T and valley splitting at 3.5 T, indicating the high quality of the 2DEGs (Fig. 2). In addition, the zeros of longitudinal magnetoresistance shows that no parallel conduction occurred in the doped layer at 0.3 K.

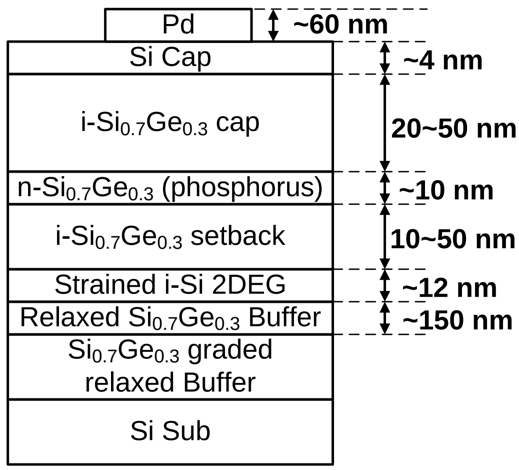


Figure 1. Cross-section schematic of a modulated-doped Si/SiGe 2DEG with a Pd surface layer for Schottky gating.

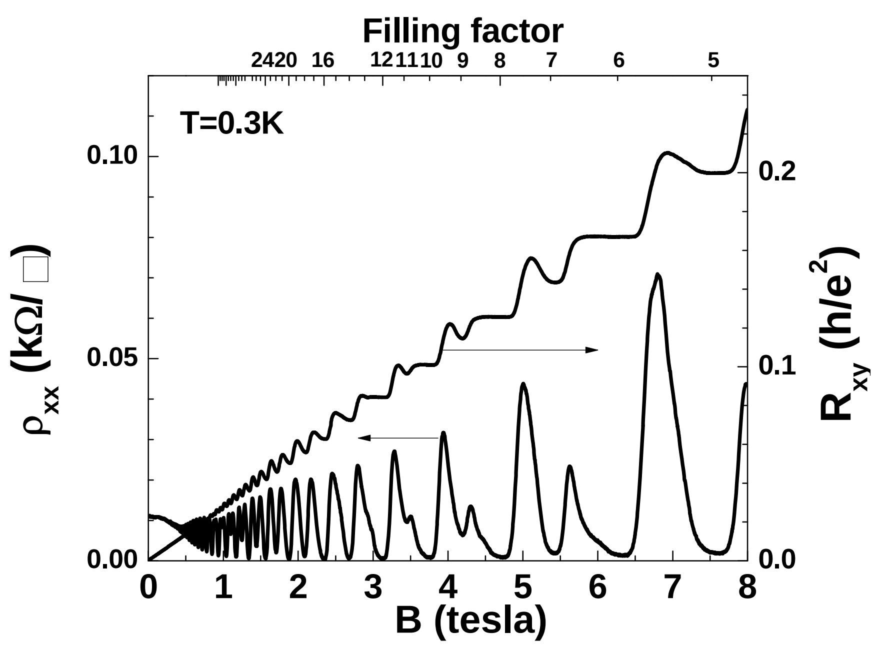


Figure 2. Longitudinal and transverse magnetoresistances of a Si 2DEG at 0.3 K. The electron density by SdH measurement was 9.1 x 10^{11} cm^{-2} and mobility was 315,000 cm^2/V-s at 0.3 K.

Low Electron Density by Modulation of 2DEG with Schottky Gating

To reach low electron density, lower doping and/or a larger setback layer is required (4). Thus, we selected a setback layer of 50 nm and doping level of 1 x 10^{18} cm^{-3}. For a Schottky gate to modulate the 2DEG density, low gate leakage is necessary. This requires low doping density at the surface, and thus a sharp turn-off of phosphorus surface segregation from the electron supply layer is necessary. By growing the $Si_{0.7}Ge_{0.3}$ cap layer at low temperature ~ 525 ^{o}C, the phosphorus segregation is significantly reduced to 13 nm/dec, and the phosphorus concentration at the surface is less than 1 x 10^{16} cm^{-3} (Fig. 3). The gate leakage current measured at 4K was extremely low (< 50 pA) up to 0.6 V (Fig. 4a). At zero bias, the Schottky gate depletes the 2DEG. The electron density of 2DEG layer can be modulated by Schottky gating at forward-bias (Fig. 4b). The capacitance extracted from the slope of Hall density vs. gate voltage is 1.0 x 10^{-7} F/cm^{-2}, reflecting the distance of 100 nm from the 2DEG layer to the surface, which can be verified by SIMS results in Fig. 3. The lowest electron density achieved by Schottky gating is 8.3 x 10^{10} cm^{-2} with mobility of 63,000 cm^2/V-s (Fig. 4c). Below this density, the 2DEG becomes insulating due to the localization from potential fluctuations resulting from the local or remote ionized dopants, or from the charges at the surface or the growth interface. As more electrons in the 2DEG layer were induced by gating, the mobility was increased due to stronger screening of the fluctuations by the electrons in the 2DEG. The mobility was enhanced by a factor of four from 63,000 to 240,000 cm^2/V-s as the electron density was increased from 8.3 x 10^{10} to 3.8 x 10^{11} cm^{-2}. Among all modulation-doped Si 2DEGs, we believe this represents the highest reported mobility for an electron density below 10^{11} cm^{-2}.

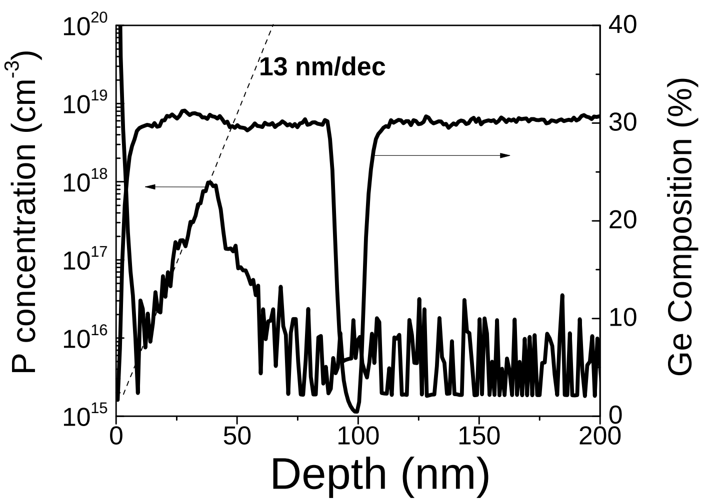
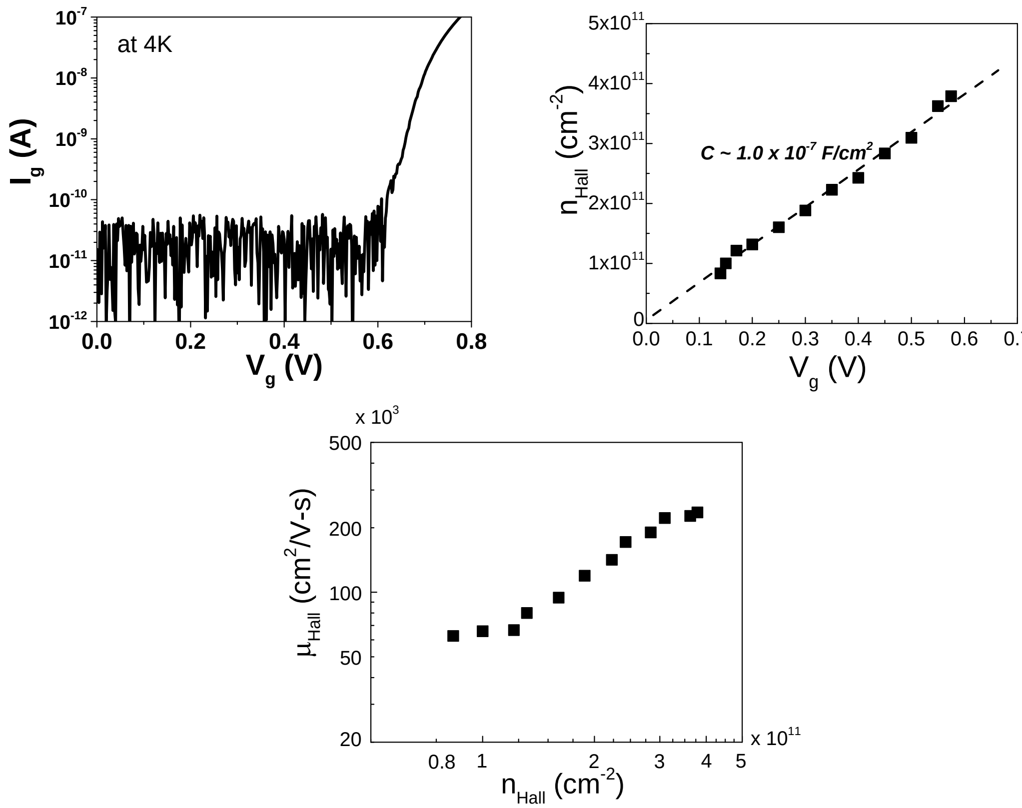


Figure 3. Ge composition (right axis) and P concentration (left axis) vs. depth from SIMS measurement.

Extremely High Electron Mobility in Si/SiGe 2DEGs

In addition to the low electron density by gating a 2DEG, we also report ungated modulation-doped Si 2DEGs of high quality. As the thickness of setback layer was varied from 10 nm to 50 nm, the electron density can be adjusted from 8 x 10^{11} cm^{-2} to 1.5 x

10^{11} cm^{-2} (Fig. 5). The highest mobility was 504,000 cm^2/V-s, with an electron density of 4 x 10^{11} cm^{-2} at 0.3 K with a thickness of setback layer is 25 nm. This is the highest among all modulated-doped Si 2DEGs grown by CVD without gating. A separate growth of a thick Si layer at 625 ^{o}C on Si substrate for SIMS measurement shows low phosphorus background level at the detection limit of 5 x 10^{13} cm^{-3}. Thus the scattering from background impurity might be minimal according to Monroe *et al*. (5). A further study is required to study the limiting factors of mobility of Si 2DEGs at low temperatures.



(c)

Figure 4. (a) Schottky gate leakage current vs. gate voltage. (b) Hall electron density vs. gate voltage. (c) Hall electron mobility vs. electron density. All data were taken at 4 K.

Summary

In summary, we demonstrated effective Schottky gating on modulation-doped Si 2DEGs by epitaxially growing a SiGe cap layer at low temperatures to reduce the surface segregation of phosphorus. We reported a low electron density of 8.3 x 10^{10} cm^{-2} with a high mobility of 63,000 cm^2/V-s. Furthermore, a very high mobility of 504,000 cm^2/V-s with density of 4 x 10^{11} cm^{-2} was also reported, the highest among ungated modulated-doped Si 2DEGs grown by CVD.

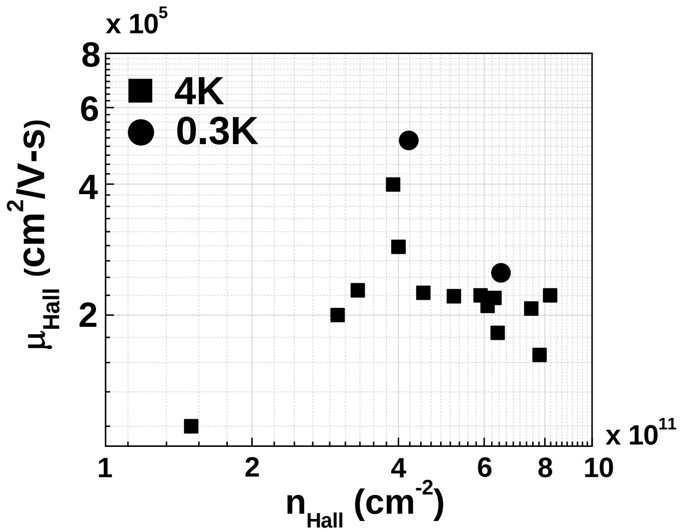


Figure 5. Hall electron mobility vs. density for multiple ungated Si 2DEGs with the setback layer thickness varied from 10 to 50 nm at 4 K and 0.3 K.

Acknowledgments

This work at Princeton University was supported by DARPA (project: HR0011-09-1-0007) and ARO (project: W911NF-09-1-0498). We also thank Amberwave, Inc. for supplying the relaxed SiGe buffer layers.

References

1. B. M. Maune, M. G. Borselli, B. Huang, T. D. Ladd, P. W. Deelman, K. S. Holabird, A. A. Kiselev, I. Alvarado-Rodrigues, R. S. Ross, A. E. Schmitz, M. Sokolich, C. A. Watson, M. F. Gyure, and A. T. Hunter, *Nature*, **481**, 344 (2012).
2. S. V. Kravchenko and M. P. Sarachik, *Rep. Prog. Phys.*, **67**, 1 (2004).
3. J. Y. Li, C. T. Huang, and J. C. Sturm, *Conf. Dig. of 6th Int. Silicon-Germanium Technol. and Dev. Mtg.*, 18 (2012).
4. C. Payette, K. Wang, P. J. Koppinen, Y. Dovzhenko, J. C. Sturm, and J. R. Petta, *Appl. Phys. Lett.*, **100**, 043508 (2012).
5. D. Monroe, Y. H. Xie, E. A. Fitzgerald, P. J. Silverman, and G. P. Watson, *J. Vac. Sci. Technol. B*, **11**(4), 1731 (1993).