Ge quantum well structure on Si with reduced thickness using growth and high-temperature diffusion

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The growth of strained Ge quantum wells is of great interest in the fabrication of gate-tunable Josephson junctions[1]. For instance, microwave-frequency superconducting circuits have recently utilized Ge-based Josephson junctions to demonstrate gate-tunable transmon qubits[2]. Historically, the epitaxial growth of high-quality strained Ge on relaxed SiGe buffers has demanded metamorphic growth[3]. To grow a metamorphic buffer with a desired lattice constant at low defect density, microns of material are generally required. Conversely, shrinking total growth thickness is necessary to streamline device fabrication; mesa-etch designs reduce loss from epilayer thickness, but, in its immediate vicinity, a tall mesa structure poses the additional issues of low lithography resolution and irregular deposition thicknesses. In this work, molecular beam epitaxy is leveraged to grow an undoped strained Ge quantum well structure with an over 90% reduction in thickness compared to previous undoped designs[4].

An alternative heterostructure is presented where 100 nm of Ge has been diffused into an undoped Si (001) substrate wafer to generate a $Si_{0.2}Ge_{0.8}$ virtual substrate. After cooling, growth nominally proceeds with a 100 nm $Si_{0.2}Ge_{0.8}$ buffer, 16 nm strained Ge quantum well, and 22 nm relaxed $Si_{0.2}Ge_{0.8}$ spacer. In a Hall bar, the hole mobility associated with the quantum well exceeds $4.4 \cdot 10^4$ $cm^2/V \cdot s$ with a sheet carrier density of $5.7 \cdot 10^{11}$ cm^{-2} at a temperature of 2 K.

The composition of the $Si_{0.2}Ge_{0.8}$ virtual substrate is verified via an asymmetric reciprocal space map, capturing a distinct SiGe peak and indicating a strained quantum well. Atomic force microscopy reveals that the surface of the sample possesses a leaf-like morphology, closely adhering to the qualities of other anneal-based designs[5]. In this thin heterostructure, a root-mean-square surface roughness of nearly 4 nm suggests that mobility is limited by the roughness of the quantum well interfaces. Further optimization in growth and anneal temperature shall be pursued in order to reduce interface roughness.

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[2] Sagi, O., Crippa, A., Valentini, M. *et al*. A gate tunable transmon qubit in planar Ge. *Nat. Commun.* **15**, 6400 (2024)

[3] Richardson, C. J. K., Lee, M.L. Metamorphic epitaxial materials. *MRS Bulletin* **41**, 193–198 (2016)

[4] Stehouwer, L., Tosato, A., Esposti, D. *et al*. Germanium wafers for strained quantum wells with low disorder. *Appl. Phys. Lett* **123**, 092101 (2023)

[5] Sigle, E., Weisshaupt, D., Oehme, M. *et al.* Strained Ge channels with high hole mobility grown on Si substrates by molecular beam epitaxy. *MIPRO* 40-44 (2021)

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Supplemental Material to Ge quantum well structure on Si with reduced thickness using growth and high-temperature diffusion

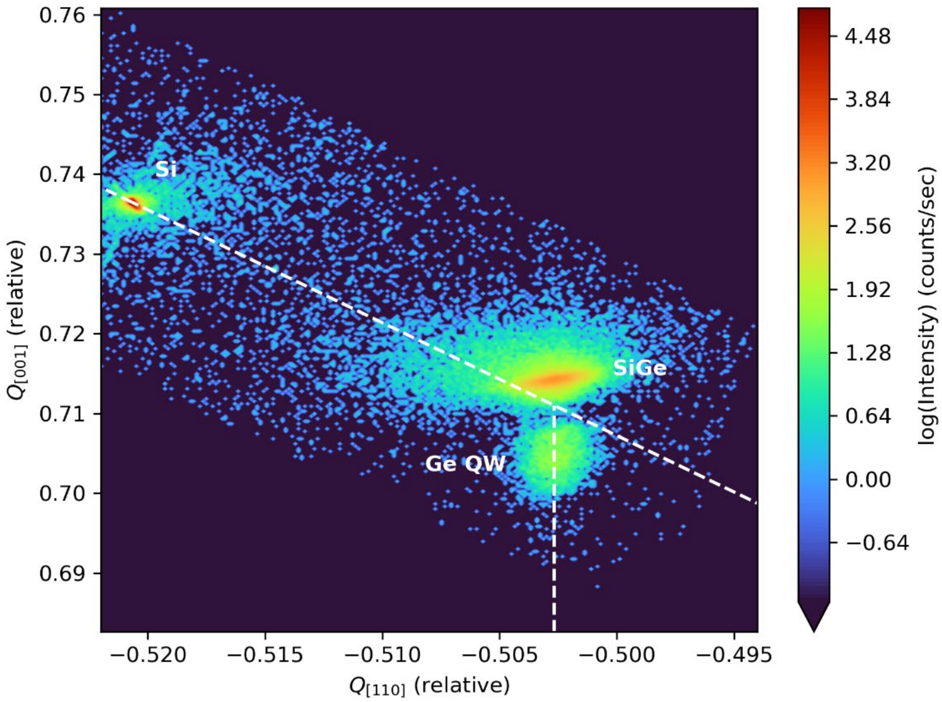

Figure S1. Reciprocal space map around the sample asymmetric $\overline{2}\overline{2}4$ peak. The diagonal, dashed line signifies a relaxed cubic lattice. The Si substrate, SiGe, and compressively strained Ge quantum well peaks are labeled. The vertical, dashed line indicates in-plane lattice matching between the SiGe and Ge layers.

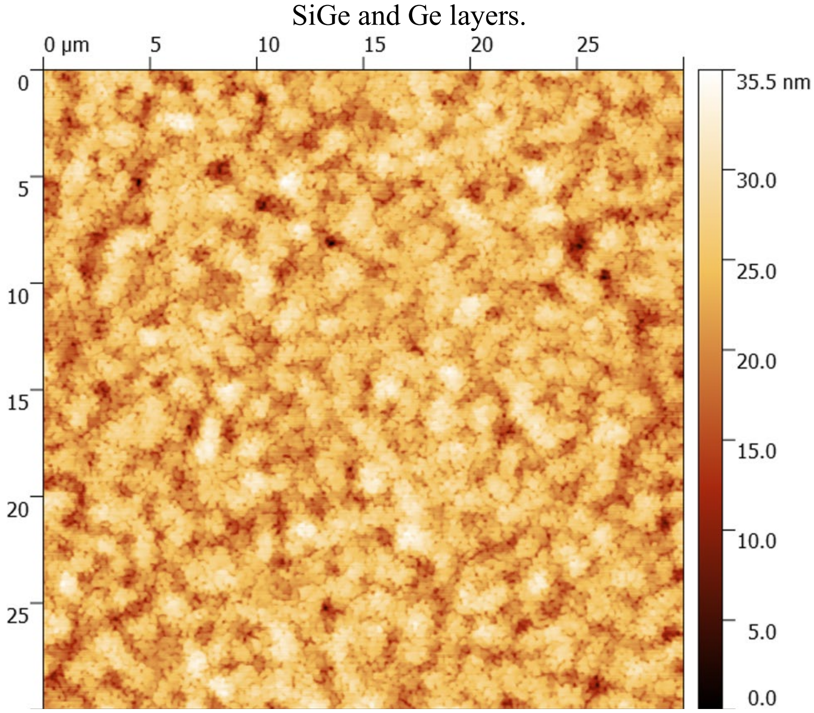

Figure S2. Atomic force micrograph of the as-grown sample surface showing an RMS roughness of 3.9 nm and peak-to-peak roughness of 35.5 nm.

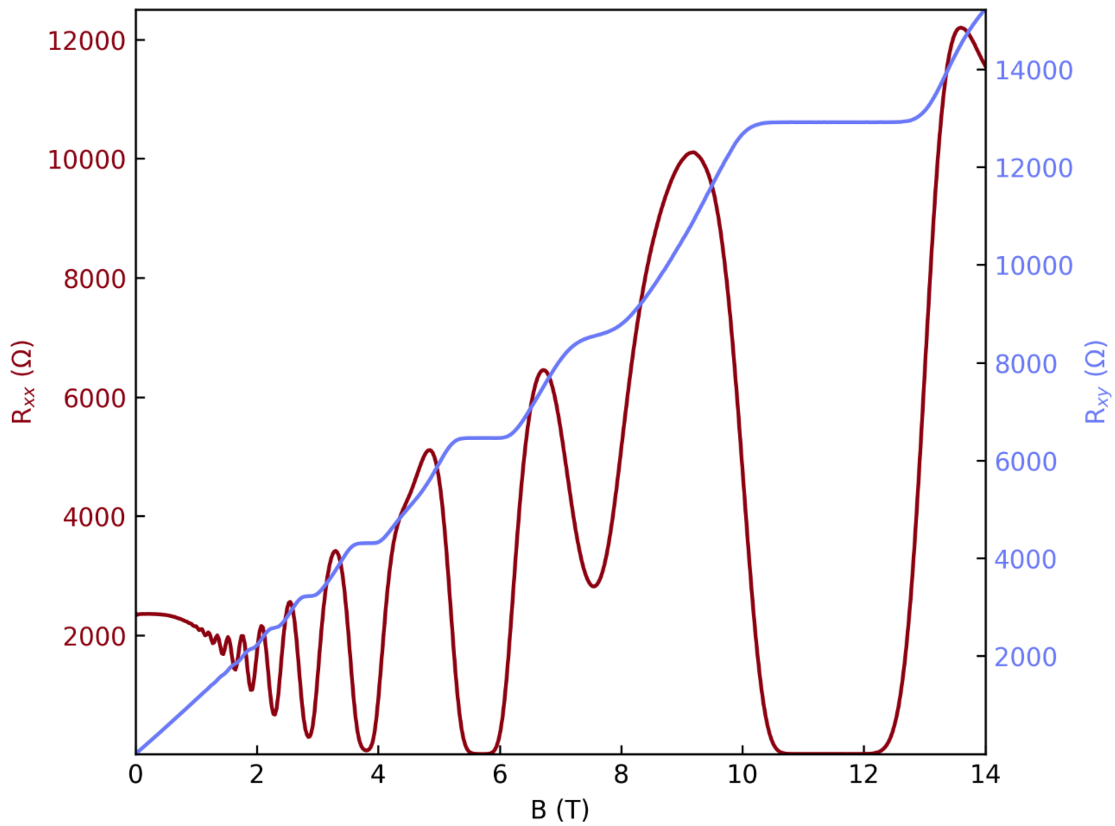

Figure S3. Longitudinal (red) and transverse (blue) Hall resistance as a function of magnetic field at 2 K with a carrier density of $5.7 \cdot 10^{11}$ cm^{-2}.

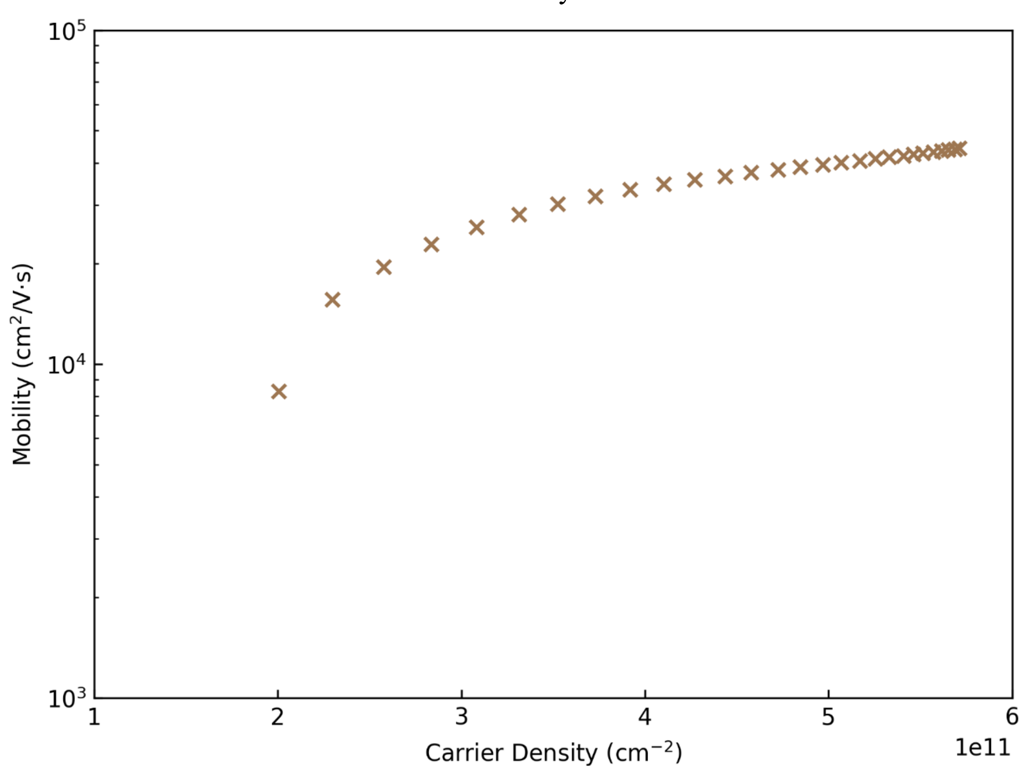

Figure S4. Gated Hall hole mobility as a function of carrier density measured at 2 K.