Group IV alloy short-range order and fluctuation effects on quantum electronics.

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Recent progress with spin quantum computing and lasers in group IV (Si, Ge and Sn) alloy heterostructures revealed alloy fluctuations and correlations that have appreciable influence on materials electronic properties [1-3]. This has inspired high-fidelity studies exploring fluctuations and short-range order across group IV alloys [3-5]. Here, short-range order (SRO) denotes atomic neighborhood correlations between alloy elements site-to-site on the diamond-type crystal lattice, whereas fluctuation denotes neighborhood statistical variations from mean composition. I will describe experiments to detect subtle nanosize alloy fluctuations and SRO, and theory and models to explain their origins and outsized effect on single-particle states for qubits in SiGe and electronic bands in SiGeSn. For electron spin qubits in SiGe heterostructures, alloy fluctuations modify splittings separating qubit states from other excited states, allowing state mixing and quantum leakage paths [3]. In SiGeSn, SRO correlations emerge above background alloy fluctuations, and this SRO is predicted to modify electronic band parameters, electronic and thermal transport, and materials design [2]. I will describe ongoing work to measure and isolate these effects and to design and control alloy fluctuations and SRO as an electronic engineering degree-of-freedom. The talk will highlight advances around the group IV epitaxial material community, through collaborations in the *Center for Manipulation of Atomic Ordering for the Manufacture of Semiconductors* (*μATOMS*) a recently funded *Energy Frontier Research Center*, and my teams work on fluctuations affecting qubit variability in SiGe materials [5].

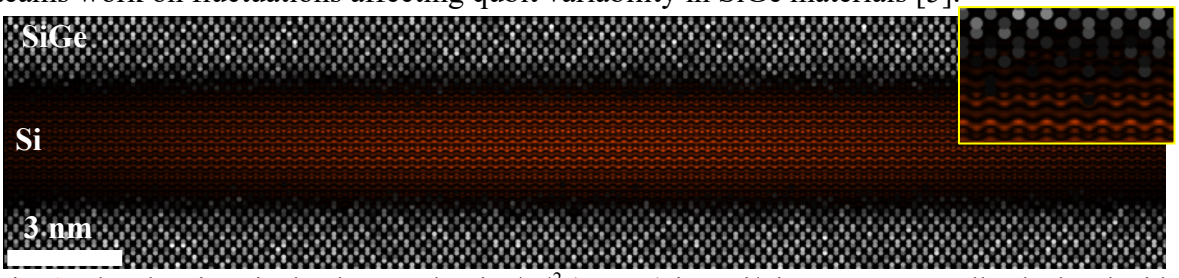

Fig. 1 Plot showing single-electron density $|\Psi|^2$ (orange) in a Si/SiGe quantum well calculated with an atomistic multivalley effective mass theory including alloy fluctuation (varied grays) shaping confinement, wavefunctions, and spectra. Inset: interface detail. From [5] under *CC Attribution 4.0*.

[1] S. Mukherjee, et al., Phys. Rev. B 95, 161402(R) (2017).
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[4] Vogl, L. M. *et al*., Science 389, 1342 (2025).
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