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13. ABSTRACT (Maximum 200 words)

This grant has provided funding for an additional graduate student, Stephen J. Robinson, to work on ARO/ARDA project DAAD-19-00-1-0407, "Controlled Coupling of Donor Atom Wavefunctions in Silicon", at the University of Illinois under the supervision of Co-PI John Tucker. Stephen's research involves fabrication of the ion-implanted contact arrays used for atom-scale STM P donor device fabrication, and low temperature measurements to characterize their properties. His efforts have been closely coordinated with T.-C. Shen, PI, and my fifth-year graduate student Jeffrey Kline working at Utah State University. Dr. Kline has recently graduated with a Ph.D. and is currently a NIST Fellow at Boulder, working to fabricate epitaxial superconductor tunnel junctions for QC experiments in that area. A portion of his salary as a graduate student was also supported by this grant. Stephen Robinson has recently moved to Utah State and will complete his Ph.D. in the coming year. He and Prof. Shen are currently working to demonstrate epitaxial single-electron transistors for use in QC spin-state detection. Both Stephen and Jeff have made very substantial contributions to demonstrating P-donor nanowires as the first step toward an integrated Si QC architecture.

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Statement of the problem studied

This grant has supported additional graduate students, Stephen Robinson and Jeff Kline, in exploring the possibilities for realizing a Kane-type quantum computer based on Si:P donor qubits. As part of a larger project, the work of these two students has centered on the following aspects of the program:

(1) UHV-STM process development for patterning P donors into Si with atomic resolution.

(2) Characterizing the electrical properties the ~1/4ML unpatterned P δ-layer.

(3) P nanowire device fabrication and electrical testing.

Summary of the most important results

(1) UHV-STM process development

A great deal of effort has been devoted to developing the UHV processes for phosphine dosing and low-temperature Si overgrowth. Technical details may be found in our publications on this subject.[1,2] The optimal overgrowth technique has yet to be defined, because accurate measurements of P atom diffusion in the growth direction are not currently available on the atomic scale. Nevertheless, considerable progress has been made in this direction and options have been defined.

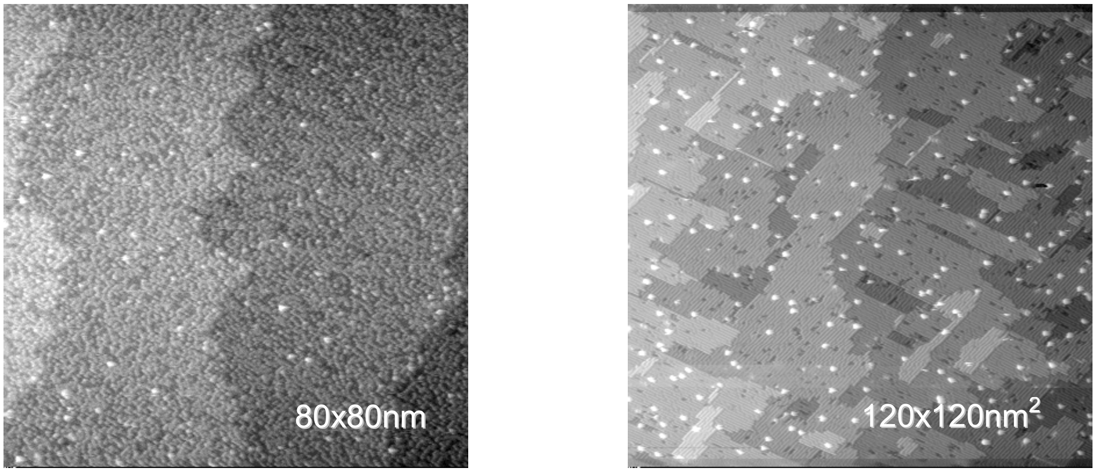

Figure 1 Atom-resolved STM images: (a) a UHV clean Si(001) surface dosed to saturation with PH_3 precursor molecules, and (b) the same sample following low-temperature Si overgrowth (bright spots are vacancies in the hydrogen termination applied to preserve the finished surface).

(2) Characterizing the ultra-dense P δ-layer

Hall effect and weak localization

Hall effect data on the unpatterned P δ-layer show a fully activated 2D electron gas up to $\sim 2\text{x}10^{14}\text{cm}^{-2}$ planar density, grown from a saturated ~0.2ML PH_3 precursor layer.[1,3] This unique 2D electron gas has properties very different from MOS inversion layers and modulation doped GaAs. Metallic conduction persists below 0.3K, and pronounced weak localization effects are observed similar to a 'dirty' metal film. The origin of this behavior is a rapid scattering rate for electrons confined tightly to the ultra-dense doping plane. This produces a multitude of closed diffusion loops that combine quantum mechanically with their time-reversed counterparts to increase resistance. An applied magnetic field reduces, and eventually eliminates, this resistive quantum interference effect of electron wavefunctions when a single flux quantum threads the area of a typical diffusion loop. Figure 2(a) illustrates the pronounced resistance peak at B=0 in magneto-transport data due to this effect. In Fig. 2(b), the same data is converted into changes in conductivity and compared to 2D weak localization theory. The result is an estimate of L ~ 150nm for the phase coherence length, over which diffusing electron wavefunctions interfere before they suffer an *in*elastic collision. Compared to the ~2nm elastic mean-free path (inferred from conductivity), the phase coherence length in the P δ-layer is surprisingly long. Because these ultra-dense 2D donor sheets are grown into the silicon crystal lattice from molecular precursors that can be patterned by e-beam, they are likely to find important applications in a future nanotechnology.

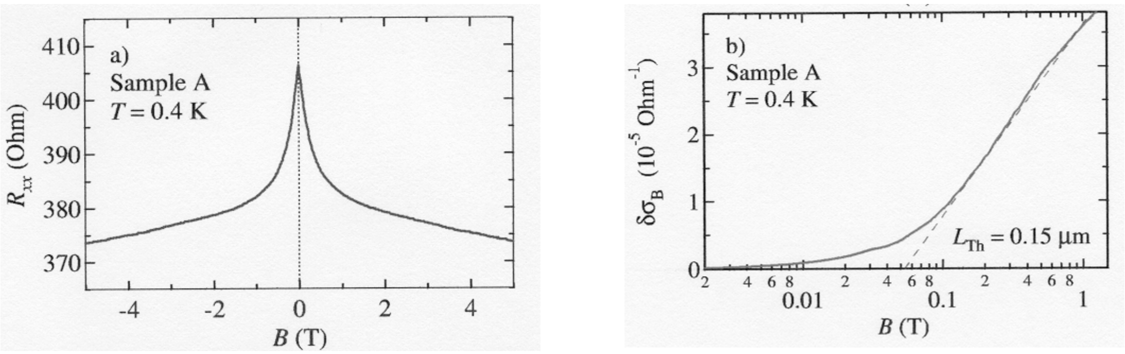

Figure 2 (a) Magneto-resistance data on the ultra-dense P δ-layer. (b) Fit of changes in conductivity to 2D weak localization theory.

(3) Nanoscale device fabrication and electrical testing

Ion-implanted contact arrays

Figure 3(a) shows a typical two-terminal device template with ion-implanted contacts and interdigitated lines. The individual lines are 0.8mm long and 1.3µm wide with 0.7µm spacing before annealing. The As$^+$ implant energy is 50keV, and dose is 0.5 to 1x10^{15} ions/cm^2. An atomic force microscopy (AFM) image is shown in Fig. 3(b). The resistance of individual implanted lines in test structures is ~20kΩ at 4K, which is within the expected range based on the implant/anneal parameters. The leakage resistance for the entire interdigitated array is typically in the GΩ range at 4K, provided the initial annealing temperature is not higher than 650ºC. The STM can therefore be positioned anywhere within the 0.8mmx0.8mm 'finger' region to pattern a nanoscale device between any pair of interdigitated contacts.[2]

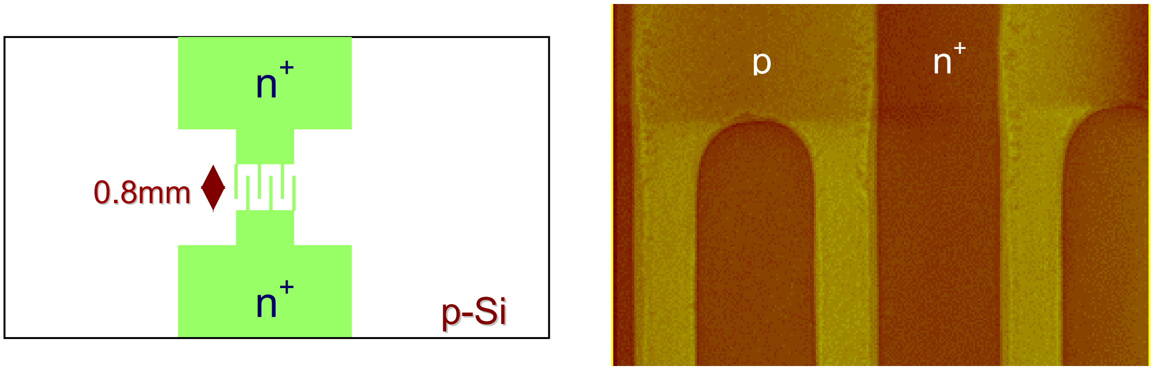

Figure 3 (a) Schematic of an ion implanted template. (b) AFM image after thermal annealing and HF etch, the As implanted fingers appear lower (darker).

Fabrication and testing of buried P donor nanowires

The first electrical devices of this kind are simple nanowires. Figure 4(a) shows one such nanowire after the STM lithography step. The bright ~33nm wide line of bare Si dangling bonds on the H-terminated Si(001) was created by multiple scanning of the STM tip at ~7V in field emission, across a 0.7μm wide gap between adjacent contact fingers. Immediately after this image was acquired, the sample was transferred to a separate chamber and dosed with PH_3 to saturation. Finally, the sample was transferred again for epitaxial Si overgrowth to a thickness of ~3nm at very low temperature.

After removal from the UHV-STM system, In solder contacts were made to the large n+ implanted contact pads at top and bottom of the sketch in Fig. 3(a). The finished sample was then mounted onto a low-temperature probe, and electrical measurements were carried out in a liquid He_3 refrigerator. Figure 4(b) shows the I-V characteristics of three such samples. Continuous P donor nanowires have been tested down to ~10nm width, but below ~30nm it has been difficult obtain ohmic behavior at low bias---most likely due to a problem of continuity at the intersections between very small nanowires and the implanted finger contacts. Magneto-resistance measurements on wires of varying width show a dramatic difference in their weak localization behavior as the wire width becomes smaller than the phase coherence length.[2]

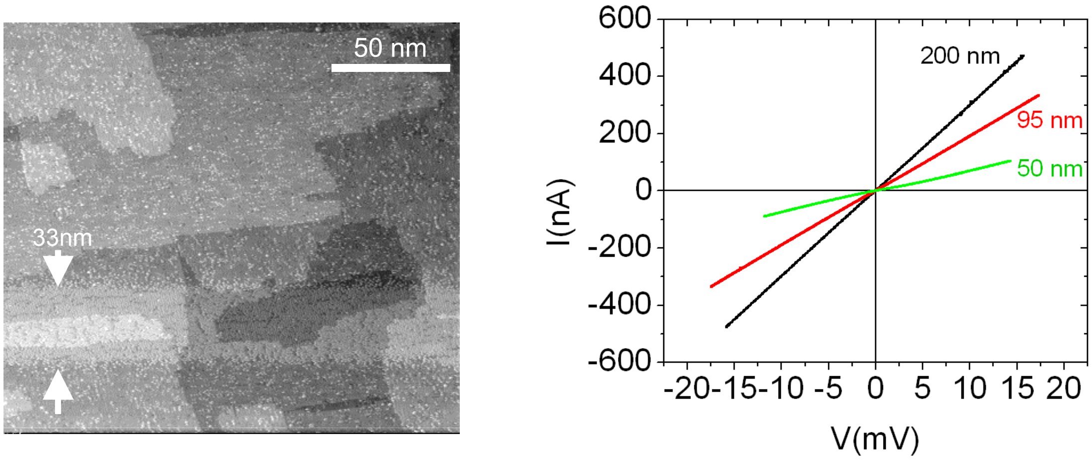

Figure 4 (a) atom-resolved STM image of a nanowire pattern after the STM lithography step to eliminate 'hydrogen resist', and prior to PH_3 dosing and Si overgrowth. (b) I-V characteristics for three finished nanowires of different widths at T=0.4K.

Successful fabrication of P donor nanowires represents an important step toward realizing epitaxial SETs that can be accurately positioned with respect to individual P atom qubits. Nanowires containing a ~10nm-wide gap are currently being fabricated for testing of planar tunnel junctions. We can now apply top-gates to these samples through a collaboration with Prof. T.-P. Ma's group at Yale. Thin SiNx dielectric films have been deposited onto our control samples at room temperature with good success, using the highly refined Jet Vapor Deposition (JVD) process. By this means, we should be able to modulate the potential barriers inside our nanowire gaps and characterize tunneling.

Listing of all publications and technical reports supported under this grant

(a) Published in journals

T.-C. Shen, J.-Y. Ji, M. A. Zudov, R.-R. Du, J. S. Kline, J. R. Tucker
"Ultradense phosphorous delta-layers grown into silicon from PH_3 molecular precursors",
Appl. Phys. Lett. 80, 1580 (2002).

J. C. Kim, J.-Y. Ji, J. S. Kline, J. R. Tucker, T.-C. Shen
"Preparation of atomically clean and flat Si(100) surfaces by low-energy ion sputtering and low-temperature annealing"
Applied Surface Science 220, 293-297 (2003).

J. C. Kim, J.-Y. Ji, J. S. Kline, J. R. Tucker, T.-C. Shen
"The role of antiphase boundaries during ion sputtering and solid phase epitaxy of Si(001)"
Surf. Sci. 538, L471 (2003).

T.-C. Shen, J. S. Kline, T. Schenkel, S. J. Robinson, J.-Y. Ji, C. Yang, R.-R. Du, J. R. Tucker
"Nanoscale electronics based on two-dimensional dopant patterns in silicon"
J. Vac. Sci. Technol. B 22(6), 3182-3185, (Nov/Dec 2004).

(b) Presented at meetings and published in the proceedings: none

(c) Presented at meetings but not published

M.A. Zudov, J. Zhang, R.R. Du, T.C. Shen, J.Y. Ji, J.S. Kline, J.R. Tucker
"Characterization of an ultra-dense 2DEG confined to a delta-layer of P in single-crystal Si"
American Physical Society March Meeting, Indianapolis, March 19, 2002.

J.S. Kline, K.F. Chen, R.Chan, M. Feng, J.R. Tucker, M.A. Zudov, R.R. Du, J.Y. Ji, J.C. Kim, T.-C. Shen
"Fabrication and characterization of dopant nanowires in silicon"
American Physical Society March Meeting, 2003.

J. R. Tucker, J. S. Kline, S. J. Robinson, M. Feng, R. Chan, T.-C. Shen, J.-Y. Ji, R.-R. Du, M. A. Zudov
"Epitaxial silicon nanodevices fabricated by P donor patterning"
IEEE 2004 Silicon Nanoelectronics Workshop, Honolulu, HI, June 13-14, 2004.

(d) Manuscripts submitted but not published

M. A. Zudov, C. L. Yang, R. R. Du, T.-C. Shen, J.-Y. Ji, J. S. Kline, J. R. Tucker,
"Weak localization in an ultradense 2D electron gas in delta-doped silicon",
submitted to Phys. Rev. B, cond-mat/0305482.

Listing of all participating scientific personnel

University of Illinois at Urbana-Champaign

Prof. J. R. Tucker, Department of Electrical and Computer Engineering (PI)
Jeffrey Kline, graduate student, M.S. 2001, Ph.D. 2005;
currently NIST Postdoctoral Fellow at Boulder, CO.
Stephen Robinson, graduate student, M.S. 2003, Ph.D. anticipated 2006.

Report of Inventions

"Silicon Field Effect Transistors Comprised of Selectively Patterned Delta-Doping Layers"

Bibliography

[1] T.-C. Shen, J.-Y. Ji, M. A. Zudov, R.-R. Du, J. S. Kline, and J. R. Tucker
"Ultradense phosphorous delta-layers grown into silicon from PH_3 molecular precursors",
Appl. Phys. Lett. 80, 1580 (2002).

[2] T.-C. Shen, J. S. Kline, T. Schenkel, S. J. Robinson, J.-Y. Ji, C. Yang, R.-R. Du, J. R. Tucker,
"Nanoscale electronics based on two-dimensional dopant patterns in silicon",
J. Vac. Sci. Technol. B 22(6), 3182-3185, (Nov/Dec 2004).

[3] M. A. Zudov, C. L. Yang, R. R. Du, T.-C. Shen, J.-Y. Ji, J. S. Kline, J. R. Tucker,
"Weak localization in an ultradense 2D electron gas in delta-doped silicon", submitted to Phys. Rev. B, cond-mat/0305482.