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Epitaxial Superconductor- semiconductor materials systems for quantum computation

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14. ABSTRACT
Our proposal was motivated by recent superconducting qubit experiments that have demonstrated single and two-qubit gate operations with fidelities exceeding 99%, placing fault tolerant quantum computation schemes within reach. On the other hand, semiconductor based devices have their own merits: fast manipulation, low-power consumption and a more direct path toward scalability. In our proposal we attemt to make hybrid superconductor on silicon devices that could have advantages of both systems cite{Tahan}. The obvious challenge is in interfacing two dissimilar materials, e.g. aluminum and silicon, with different material and electronic properties.
Group IV semiconductors including Si could offer feasible platforms for
implementation of single-material hybrid quantum systems. With the wealth of knowledge on materials synthesis and micro-/nano-fabrication of Si based devices, We studied superconductivity in heavily-doped Si, achieving all-Si to achieve hybrid superconductor-semiconductor systems with improved coherence times. We have shown superconductivity of gallium doped Silicon is possible both with ion implantation.We attempted fabrication of resonators for qubit readouts in all Si substrates. We have performed structural analysis of interface between doped and undoped Silicon films to improve the quality of qubit circuits.

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Title: (YIP) Epitaxial Superconductor-semiconductor materials systems for quantum computation

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Motivation and Background

Our proposal was motivated by recent superconducting qubit experiments that have demonstrated single and two-qubit gate operations with fidelities exceeding 99%, placing fault tolerant quantum computation schemes within reach. On the other hand, semiconductor based devices have their own merits: fast manipulation, low-power consumption and a more direct path toward scalability. In our proposal we attemt to make hybrid superconductor on silicon devices that could have advantages of both systems [2]. The obvious challenge is in interfacing two dissimilar materials, e.g. aluminum and silicon, with different material and electronic properties.

Group IV semiconductors including Si could offer feasible platforms for implementation of single-material hybrid quantum systems. With the wealth of knowledge on materials synthesis and micro-/nano-fabrication of Si based devices, We studied superconductivity in heavily-doped Si, achieving all-Si to achieve hybrid superconductor-semiconductor systems with improved coherence times. We have shown superconductivity of gallium doped Silicon is possible both with ion implantation.We attempted fabrication of resonators for qubit readouts in all Si substrates. We have performed structural analysis of interface between doped and undoped Silicon films to improve the quality of qubit circuits.

1 Technical Achievements

In this project we focused on observation of superconductivity in Silicon substrates by heavy p-doping, in order to realize superconductor-seminconductor hybrid devices. There were two general approaches were used to realize superconductivity in Si : 1) Top-down approach using Ga+ implantation; 2) Bottom-up approach via molecular beam homoepitaxy. This project highlights the possibility of observing superconductivity in such systems. However, since observation of superconductivity requires doping beyond equilibrium solubility limits,the resulting superconductors may be highly disordered. This necessitates a close combination of materials growth and device characterization in order optimize the DC and RF characteristics of the resulting superconductor-semiconductor interfaces. Here is a summary of the two approaches used to prepare superconducting Si:

1.1 Top-down approach: Ion implantation

The term top-down is used for approaches where superconductivity is induced in already-grown substrates such as floating-zone grown prime Si wafers. The most common approach in between top-down methods is to use medium-energy ion implantation. Superconductivity in both Si substrates using Ga+ implantation between 80 and 100 keV has been observed . It appears that Ga clustering right below the SiO_2 barrier is the main cause for the superconducting behavior. However, the implantation parameter phase space was not fully explored, including the various implantation energies and fluence levels. Those parameters would directly vary the depth and Ga concentration of the heavily doped layer, therefore varying its stoichiometry and structure. Fig.1 shows the results from the Monte Carlo simulation of Ga+ implantation in Si and Ge as a function of implantation energy. The fluence was fixed at 4 x $10^{16} cm^{-2}$. Considering that there will be a damage layer beyond the depth of the superconducting thin film, one should attempt to minimize this layer in order to prevent extra resistive elements in the eventual junction.

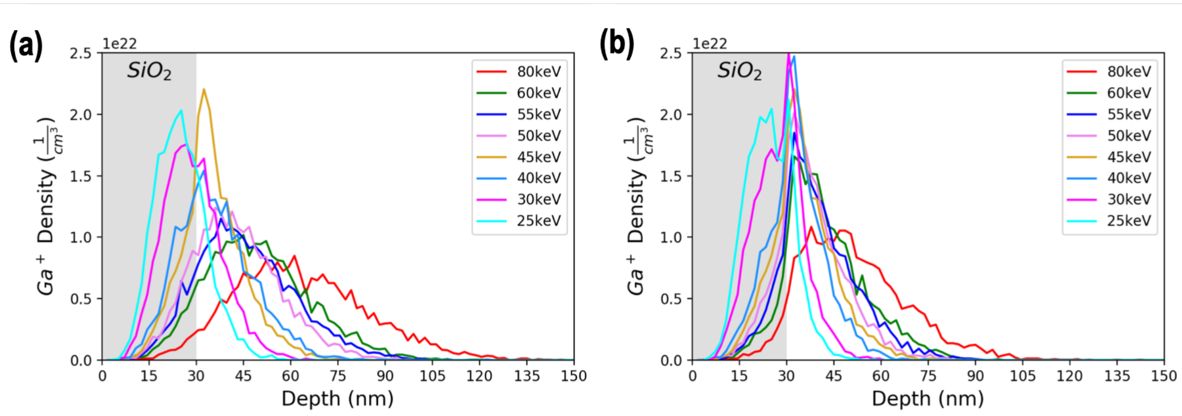

Figure 1: MC simulations of Ga implantation in Si and Ge

The transport properties of these films together with cross sectional images are shown in Fig 2. We observe an insulating behavior in samples that are annealed below 500 C while a superconducting phase with critical temperature of 6-7 K for higher annealing temperatures. The magnetic field reveals a very large critical magnetic field out-of-the-plane (10 T) and in-plane (16 T). Cross sectional TEM images show Gallium clusters that penetrate up to 150 nm below the surface with average distance of less than 7 nm.

n order to realize superconducting resonators with long lifetimes on group IV materials platforms (i.e. Si), superconductivity should be directly realized in the semiconducting substrates. The process begins with deposition of a top diffusion barrier layer (i.e. oxide, nitride or metal) followed by high-energy, high-fluency implantation of group III ions into the group IV matrix. After ion implantation, samples were subjected a dopant activation process that includes annealing

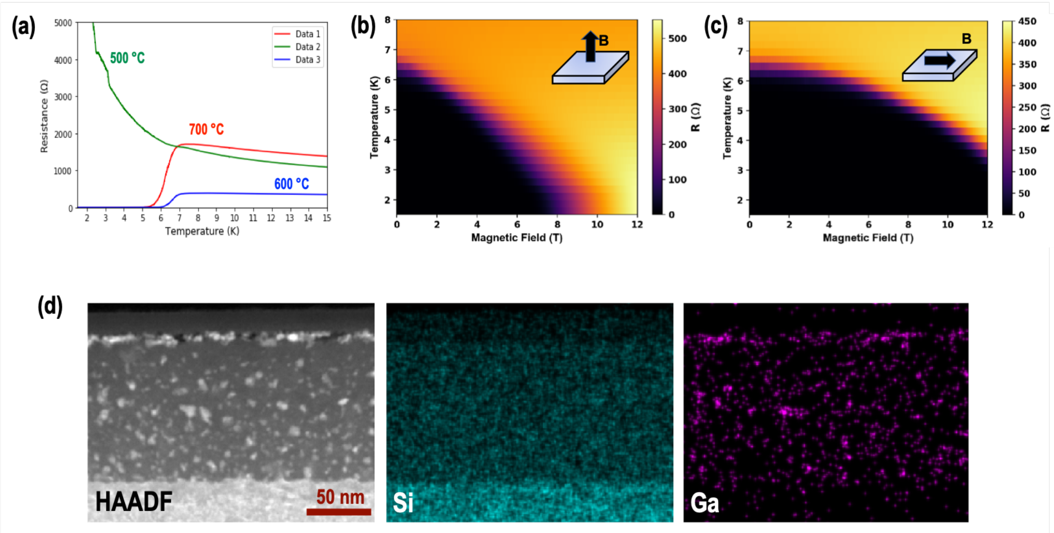

Figure 2: Data on the ion implanted Si superconductivity

at 500800 ^{o}C under continues inert gas flow. We have done a systematic study of this process and identified the window that superconductivity is most stable. We fabricated inear and spiral microwave resonators spanning a range of device aspect ratios to systematically explore materials- and process-induced sources of microwave dissipation associated with the fabrication and interface. Resonators made out of ion implanted Si showed an insulating behavior at 20 mK. We found with many tries that superconductivity in Si is very fragile and disappears below 100 mK. This was not the case for ion implanted Germanium. However Ge substrates tend to be leaky and not suitable for devices.

1.2 Bottom-up approach: Thin-film deposition

The second approach would include depositing thin layers of heavily doped Si on semi-insulating substrates. A variant this method, with a gas phase dopant BCl_3 has been previously used to demonstrate the first superconducting Si sample. However, this method locally melts the Si, incorporated B inside and recrystallize the layer. Therefore, is it not quite a bottom-up approach, although the instrumentation appears to be a deposition-like system.

To achieve the direct growth of a thin superconducting layer our team have used co-deposition of Si with very high Ga fluxes. A variation of deposition parameters including the Ga fluxes, deposition temperature and surface pre-clean conditions have been tested. We have grown buffer layers of Si [111] and [001] on same crystal Si using our MBE system shown in Fig. 3. Two sets of wafers have been introduced in the chamber. One set without any treatment and one set dipped in buffered HF acid. Wafers are heated until a visible RHEED pattern becomes visible. RHEED images are shown in Fig .4, for an example run.

Our transport properties did not show the superconducting transition. However, the AC magentic susceptibility indicated a superconducting transition at 6 K. This confirms that superconductivity exists within the sample. However, a freeze-out is possibly occurring not showing clear transport signature of the superconductor. WE should note that our cross sectional TEM imaging of the MBE grown films does not show clustering like ion implantation. As it is clear in Fig. 4 we could grow conducting Si wafer by lowering the Schottky barrier just enough to make ohmic contact Using homoepitaxy, stacks of superconducting and non-superconducting structures could be synthesized, allowing for vertical junctions. Unfortunately since we did not observe superconductivity in transport we could not make these type of devices.

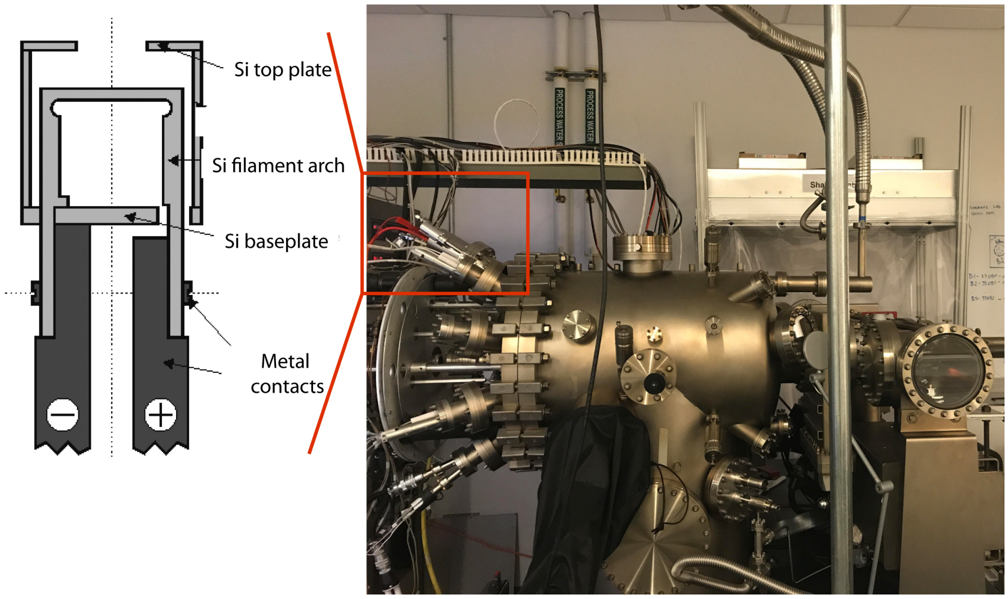

Figure 3: A photo of our molecular beam epitaxy machine and the schematic of our silicon source. The filament is made of Si that slowly evaporates. In this design it is possible to explore isotropically pure Silicon deposition as well.

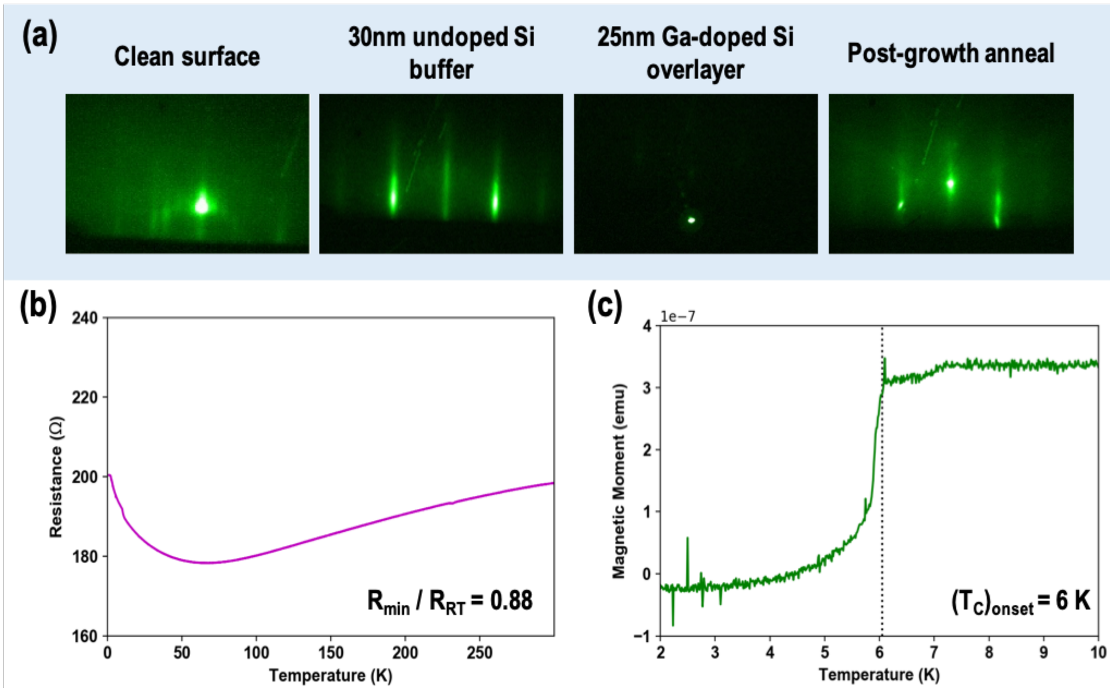

Figure 4: Silicon homoepitaxy results

2 Organizing Conferences and symposiums

1 . April 2019 Javad with Sebastian Will and Doug McClure organize the first joint quantum symposium NYU-Columbia-Flatiron, New York, NY.

2 . April 2019 Javad organizing Materials Research Society symposium on emerging materials for quantum information, Phoenix, AZ. (Scientific Program)

3 Publications involving PI since Sept 2018

1. William Mayer, William F. Schiela, Joseph Yuan, Mehdi Hatefipour, Wendy L. Sarney, Stefan P. Svensson, Asher C. Leff, Tiago Campos, Kaushini S. Wickramasinghe, Matthieu C.

Dartiailh, Igor Zutic, Javad Shabani, Superconducting proximity effect in InAsSb surface quantum wells with in-situ Al contact, preprint available at arXiv:1909.12571 (2019).

2. Tong Zhou, Matthieu C. Dartiailh, William Mayer, Jong E. Han, Alex Matos-Abiague, Javad Shabani, Igor Zutic, Phase Control of Majorana Bound States in a Topological X Junction, preprint available at arXiv:1909.05386 (2019).
3. William Mayer, Matthieu C. Dartiailh, Joseph Yuan, Kaushini S. Wickramasinghe, Alex Matos-Abiague, Igor uti, Javad Shabani, Phase signature of topological transition in Josephson Junctions, preprint available at arXiv:1906.01179 (2019).
4. William Mayer, Matthieu C. Dartiailh, Joseph Yuan, Kaushini S. Wickramasinghe, Enrico Rossi, and Javad Shabani, Gate Controlled Anomalous Phase Shift in Al/InAs Josephson Junctions, preprint available at arXiv:1905.12670 (2019).
5. Feng Wen, Javad Shabani, and Emanuel Tutuc, Josephson Junction Field-effect Transistors for Boolean Logic Cryogenic Applications, preprint available at arXiv:1905.13008 (2019).
6. Narayan Mohanta, Tong Zhou, Junwen Xu, Jong E. Han, Andrew D. Kent, Javad Shabani, Igor Zutic, Alex Matos-Abiague, Electrical control of Majorana bound states using magnetic stripes, Phys. Rev. Applied, 12, 034048 (2019).
7. Natalia Pankratova, Hanho Lee, Roman Kuzmin, Maxim Vavilov, Kaushini Wickramasinghe, William Mayer, Joseph Yuan, J. Shabani, Vladimir E Manucharyan, The multi-terminal Josephson effect, preprint available at arXiv:1812.06017 (2018).
8. Y. Sato, S. Matsuo, C.-H. Hsu, P. Stano, K. Ueda, Y. Takeshige, H. Kamata, J. S. Lee, B. Shojaei, K. Wickramasinghe, J. Shabani, C. Palmstrom, Y. Tokura, D. Loss, S. Tarucha, Strong Electron-Electron Interactions of a Tomonaga Luttinger Liquid Observed in InAs Quantum Wires, Phys. Rev. B 99, 155304 (2019).
9. D. T. Liu, J. Shabani, A. Mitra, Floquet Majorana zero and pi modes in planar Josephson junctions, Phys. Rev. B 99, 094303 (2019).
10. W. Mayer, J. Yuan, K. Wickramasinghe, T. Nguyen, M. Dartiailh, J. Shabani, Superconducting proximity effect in epitaxial Al-InAs heterostructures, Appl. Phys. Lett. 114, 103104 (2019). (Featured)
11. W. L. Sarney, S. P. Svensson, K. S. Wickramasinghe, J. Yuan, J. Shabani, Reactivity studies and structural properties of Al on compound semiconductor surfaces, Journal of Vacuum Science & Technology B 36, 062903 (2018).
12. D. T Liu, J. Shabani, A. Mitra, Long-range Kitaev Chains via Planar Josephson Junctions, Phys. Rev. B 97, 235114 (2018).

4 PI's Talks and Colloquiums

1. (invited) Workshop on Enabling Quantum Leap-Braiding and Fusing Majoranas, University of Maryland, MD (2019)
2. (Panelist) Quantum Computation: What Device Platform will Reign Supreme? at 77th Device Research Conference, Michigan Ann Arbor, MI (2019)
3. McGill University, Physics Department Condensed Matter Seminars, Montreal, QC (2019)
4. IBM Q Summit, How to Teach Quantum (Education Workshop) Yorktown Heights, NY (2019)
5. (invited) 2nd Joint Quantum Symposium at Columbia University (2019)
6. (invited) University of Texas, Dallas, Physics Department colloquium, Dallas, TX (2019)
7. (lecture) Fundamentals of Quantum Materials Winter School and Workshop at University of Maryland, College Park, MD (2019)

8. (invited) PCSI 46th Conference on the Physics and Chemistry of Surfaces and Interfaces, New Mexico, NM (2019)
9. (Colloquium) University of Rochester, Physics Department colloquium, Rochester NY (2018)
10. (Colloquium) William and Mary university, Physics Department colloquium, Williamsburg VA (2018)
11. (invited) Rutgers , Physics Department condensed matter seminars, Piscataway, NJ (2018)
12. (Colloquium) City Tech CUNY, Physics Department seminars, Brooklyn, NY (2018)
13. (invited) Center for Functional NanoMaterials at Brookhaven National Laboratory, NY (2018)
14. (invited) PIRE:HYBRID NSF Hybrid symposium, Pittsburgh, PA(2018)
15. (invited) Penn State University, Physics Department CAMP seminars, PA.
16. (invited) New Trends in Topological Insulators and International Conference on Narrow Gap Semiconductors Luxembourg (2018)
17. (Lecture) Device Research Conference, Santa Barbara, CA (2018)
18. (Invited) Compound Semiconductor Week (CSW) Conference, MIT, Boston, MA (2018

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