

# the foundation of an impending revolution



**Meenakshi Singh**  
Sandia National Laboratories





# the foundation of an impending revolution

in  
electronics

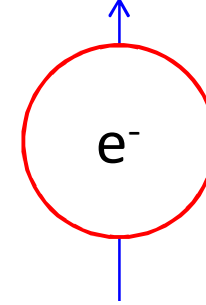


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# Prologue: do we want a revolution?

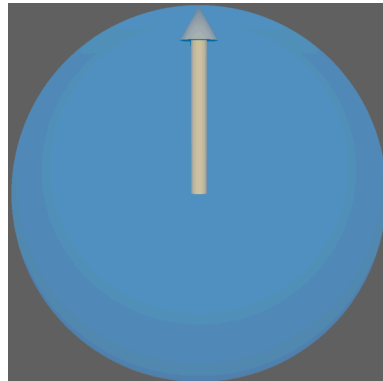
Conventional electronics rely on the charge of an electron

Electron has another property - spin

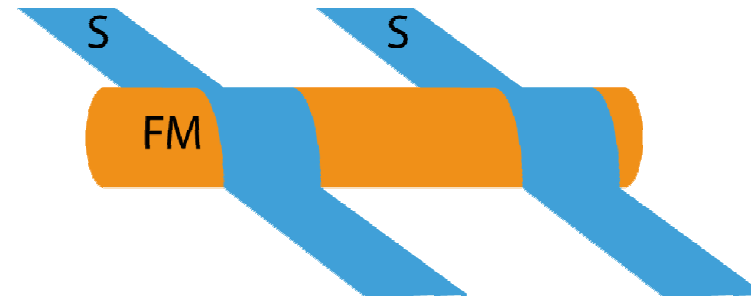


- End of 'Moore's Law' is coming
- Multiple functionality
- ...
- ...

## Donor Spin Qubits in Silicon



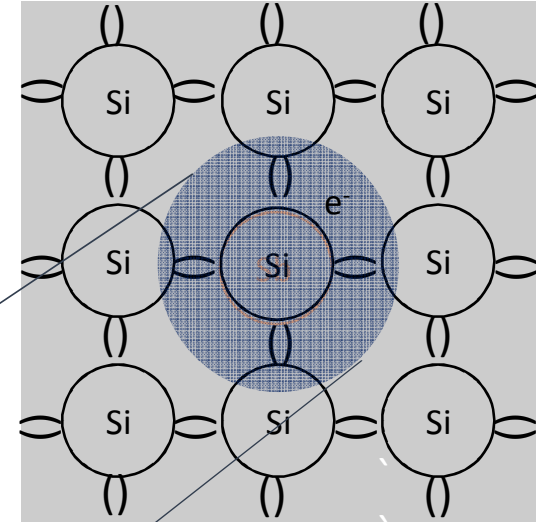
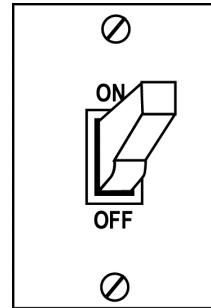
## Proximity Effect in Ferromagnetic Nanowires



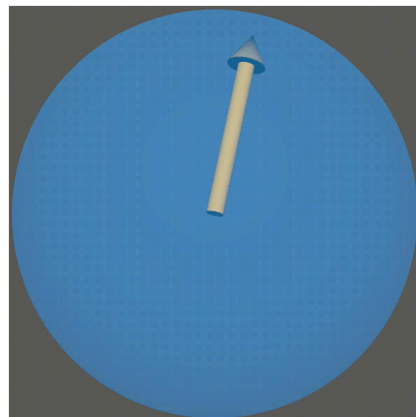
# Donor Spin Qubits in Silicon

# Donor Spin Qubits in Silicon

A bit



An electron spin



|                                |                                 |                                |                                 |                                 |                                 |                                    |                                 |                                 |                                 |                                 |                                  |                                |                                  |                                  |                                 |                                    |                                 |                                 |                             |                                |                             |
|--------------------------------|---------------------------------|--------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|--------------------------------|----------------------------------|----------------------------------|---------------------------------|------------------------------------|---------------------------------|---------------------------------|-----------------------------|--------------------------------|-----------------------------|
| hydrogen<br>1<br>H<br>1.0079   |                                 |                                |                                 |                                 |                                 |                                    |                                 |                                 |                                 |                                 |                                  |                                |                                  |                                  |                                 |                                    | helium<br>2<br>He<br>4.0026     |                                 |                             |                                |                             |
| lithium<br>3<br>Li<br>6.941    | beryllium<br>4<br>Be<br>9.0122  |                                |                                 |                                 |                                 |                                    |                                 |                                 |                                 |                                 |                                  |                                |                                  |                                  |                                 | boron<br>5<br>B<br>10.811          | carbon<br>6<br>C<br>12.011      | nitrogen<br>7<br>N<br>14.007    | oxygen<br>8<br>O<br>15.999  | fluorine<br>9<br>F<br>18.998   | neon<br>10<br>Ne<br>20.180  |
| sodium<br>11<br>Na<br>22.990   | magnesium<br>12<br>Mg<br>24.305 |                                |                                 |                                 |                                 |                                    |                                 |                                 |                                 |                                 |                                  |                                |                                  |                                  |                                 | aluminum<br>13<br>Al<br>26.982     | silicon<br>14<br>Si<br>28.086   | phosphorus<br>15<br>P<br>30.974 | sulfur<br>16<br>S<br>32.065 | chlorine<br>17<br>Cl<br>35.453 | argon<br>18<br>Ar<br>39.948 |
| potassium<br>19<br>K<br>39.098 | calcium<br>20<br>Ca<br>40.078   | scandium<br>21<br>Sc<br>44.956 | titanium<br>22<br>Ti<br>47.867  | vanadium<br>23<br>V<br>50.942   | chromium<br>24<br>Cr<br>51.996  | manganese<br>25<br>Mn<br>54.938    | iron<br>26<br>Fe<br>55.845      | cobalt<br>27<br>Co<br>58.933    | nickel<br>28<br>Ni<br>58.693    | copper<br>29<br>Cu<br>63.546    | zinc<br>30<br>Zn<br>65.39        | gallium<br>31<br>Ga<br>69.723  | germanium<br>32<br>Ge<br>72.61   | arsenic<br>33<br>As<br>74.922    | selenium<br>34<br>Se<br>78.96   | bromine<br>35<br>Br<br>79.904      | krypton<br>36<br>Kr<br>83.80    |                                 |                             |                                |                             |
| rubidium<br>37<br>Rb<br>85.468 | strontium<br>38<br>Sr<br>87.62  | yttrium<br>39<br>Y<br>88.906   | zirconium<br>40<br>Zr<br>91.224 | niobium<br>41<br>Nb<br>92.906   | molybdenum<br>42<br>Mo<br>95.94 | technetium<br>43<br>Tc<br>[98]     | ruthenium<br>44<br>Ru<br>101.07 | rhodium<br>45<br>Rh<br>102.91   | palladium<br>46<br>Pd<br>106.42 | silver<br>47<br>Ag<br>107.87    | cadmium<br>48<br>Cd<br>112.41    | indium<br>49<br>In<br>114.82   | tin<br>50<br>Sn<br>118.71        | antimony<br>51<br>Sb<br>121.76   | tellurium<br>52<br>Te<br>127.60 | iodine<br>53<br>I<br>126.90        | xenon<br>54<br>Xe<br>131.29     |                                 |                             |                                |                             |
| cesium<br>55<br>Cs<br>132.91   | barium<br>56<br>Ba<br>137.33    | 57-70<br>*                     |                                 | lanthanum<br>57<br>La<br>138.91 | cerium<br>58<br>Ce<br>140.12    | praseodymium<br>59<br>Pr<br>140.91 | neodymium<br>60<br>Nd<br>144.24 | promethium<br>61<br>Pm<br>[145] | samarium<br>62<br>Sm<br>150.36  | europtium<br>63<br>Eu<br>151.96 | gadolinium<br>64<br>Gd<br>157.25 | terbium<br>65<br>Tb<br>158.93  | dysprosium<br>66<br>Dy<br>162.50 | holmium<br>67<br>Ho<br>164.93    | erbium<br>68<br>Er<br>167.26    | thulium<br>69<br>Tm<br>168.93      | ytterbium<br>70<br>Yb<br>173.04 |                                 |                             |                                |                             |
| francium<br>87<br>Fr<br>[223]  | radium<br>88<br>Ra<br>[226]     | 89-102<br>**                   |                                 | actinium<br>89<br>Ac<br>[227]   | thorium<br>90<br>Th<br>232.04   | protactinium<br>91<br>Pa<br>231.04 | uranium<br>92<br>U<br>238.03    | neptunium<br>93<br>Np<br>[237]  | plutonium<br>94<br>Pu<br>[244]  | americium<br>95<br>Am<br>[243]  | curium<br>96<br>Cm<br>[247]      | berkelium<br>97<br>Bk<br>[247] | californium<br>98<br>Cf<br>[251] | einsteinium<br>99<br>Es<br>[252] | fermium<br>100<br>Fm<br>[257]   | mendelevium<br>101<br>Md<br>[258]  | nobelium<br>102<br>No<br>[259]  |                                 |                             |                                |                             |
|                                |                                 |                                |                                 |                                 |                                 |                                    |                                 |                                 |                                 |                                 |                                  |                                |                                  |                                  |                                 | ununquadium<br>114<br>Uuq<br>[289] |                                 |                                 |                             |                                |                             |

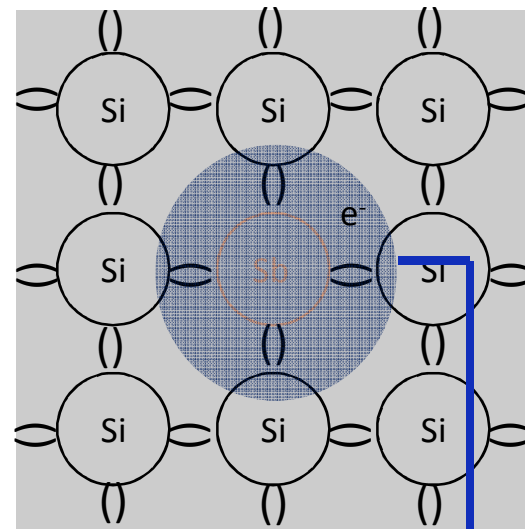
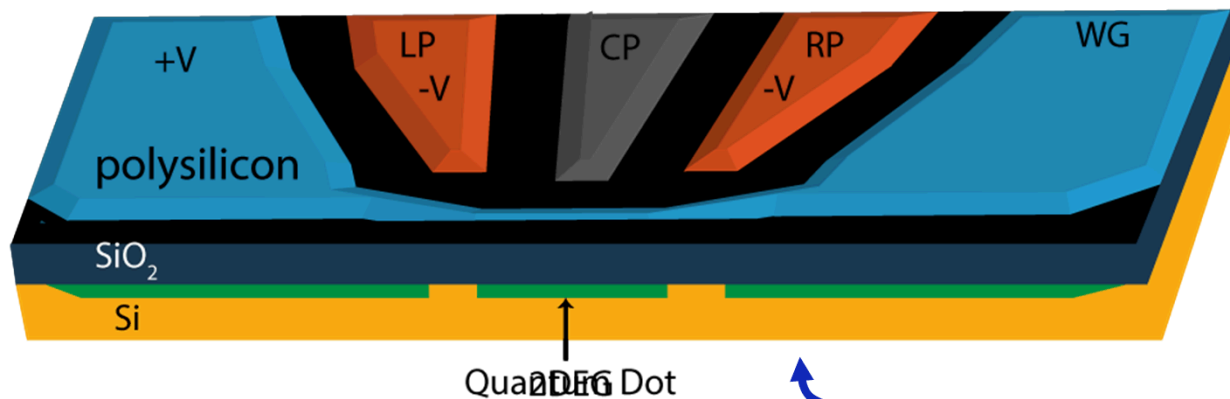
\* Lanthanide series

\*\* Actinide series

|                                 |                               |                                    |                                 |                                 |                                |                                 |                                  |                                |                                  |                                  |                               |                                   |                                 |
|---------------------------------|-------------------------------|------------------------------------|---------------------------------|---------------------------------|--------------------------------|---------------------------------|----------------------------------|--------------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------------|---------------------------------|
| lanthanum<br>57<br>La<br>138.91 | cerium<br>58<br>Ce<br>140.12  | praseodymium<br>59<br>Pr<br>140.91 | neodymium<br>60<br>Nd<br>144.24 | promethium<br>61<br>Pm<br>[145] | samarium<br>62<br>Sm<br>150.36 | europtium<br>63<br>Eu<br>151.96 | gadolinium<br>64<br>Gd<br>157.25 | terbium<br>65<br>Tb<br>158.93  | dysprosium<br>66<br>Dy<br>162.50 | holmium<br>67<br>Ho<br>164.93    | erbium<br>68<br>Er<br>167.26  | thulium<br>69<br>Tm<br>168.93     | ytterbium<br>70<br>Yb<br>173.04 |
| actinium<br>89<br>Ac<br>[227]   | thorium<br>90<br>Th<br>232.04 | protactinium<br>91<br>Pa<br>231.04 | uranium<br>92<br>U<br>238.03    | neptunium<br>93<br>Np<br>[237]  | plutonium<br>94<br>Pu<br>[244] | americium<br>95<br>Am<br>[243]  | curium<br>96<br>Cm<br>[247]      | berkelium<br>97<br>Bk<br>[247] | californium<br>98<br>Cf<br>[251] | einsteinium<br>99<br>Es<br>[252] | fermium<br>100<br>Fm<br>[257] | mendelevium<br>101<br>Md<br>[258] | nobelium<br>102<br>No<br>[259]  |

# What is a spin to do? (to be a viable qubit)

1. Take orders from and give information to user: single qubit

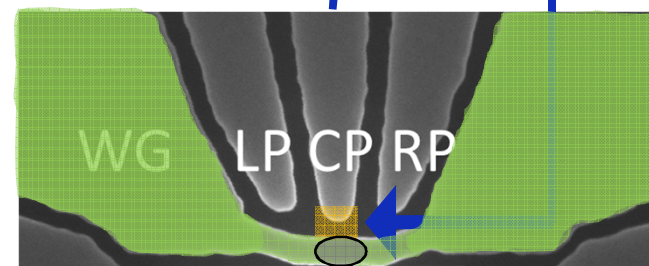


2. Work with other spins: two qubit gates

Deterministic control over:

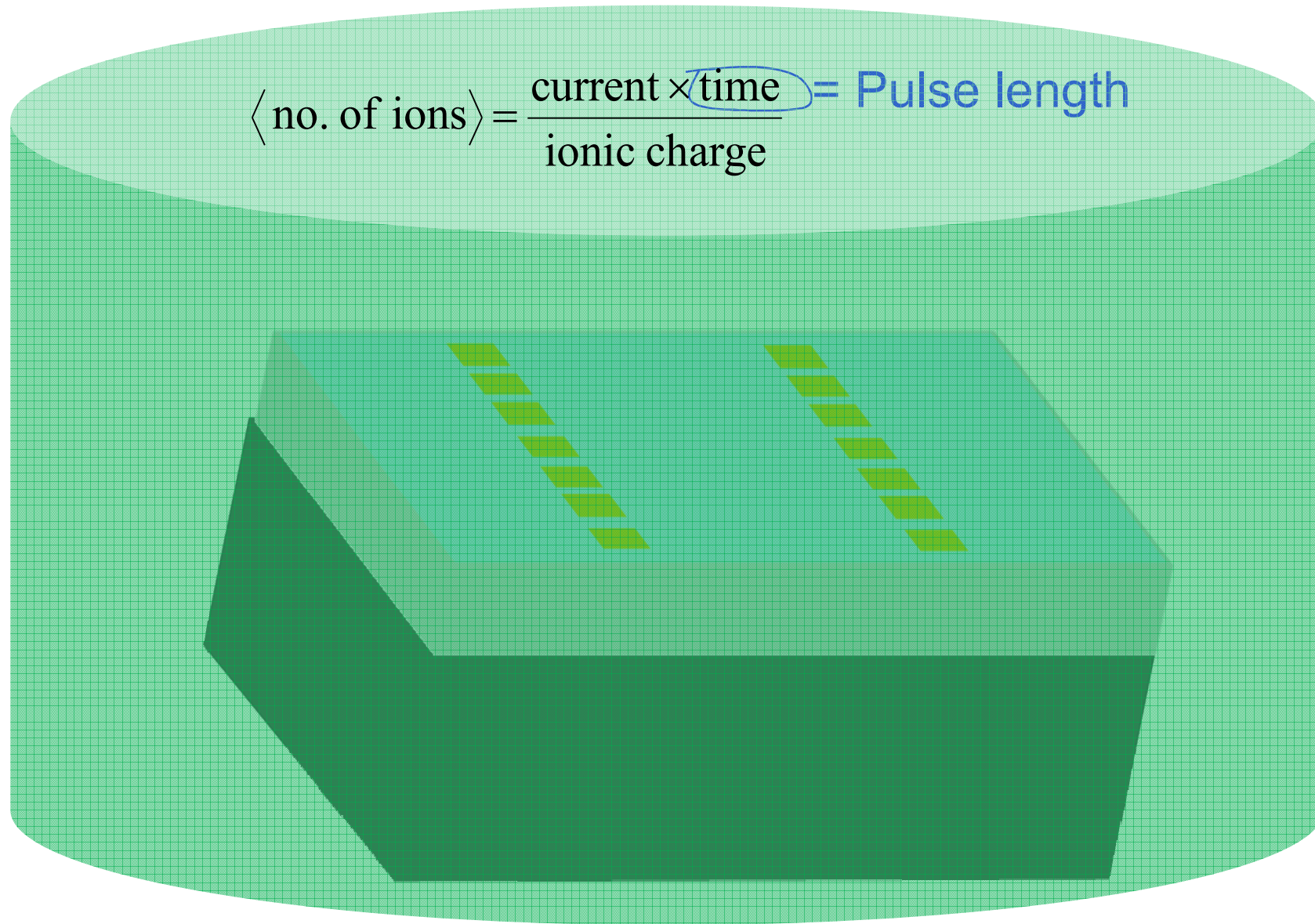
1. Placement of donors

2. Number of donors



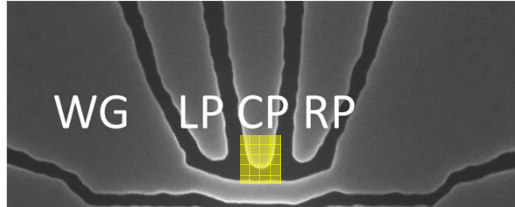
500 nm

# How the location/"counting" was done till now

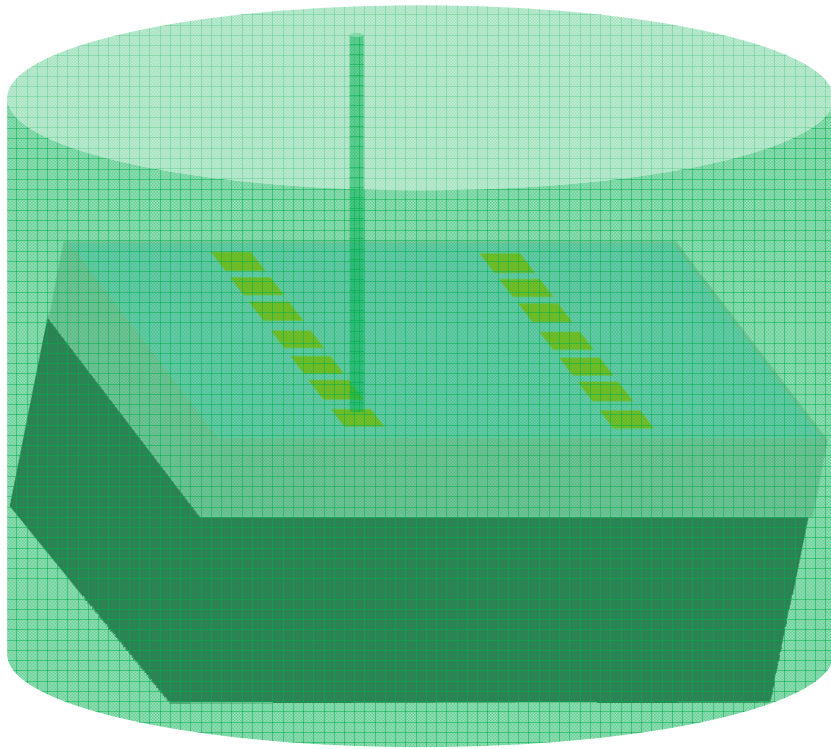


# How we control donor location

## Defining lateral position

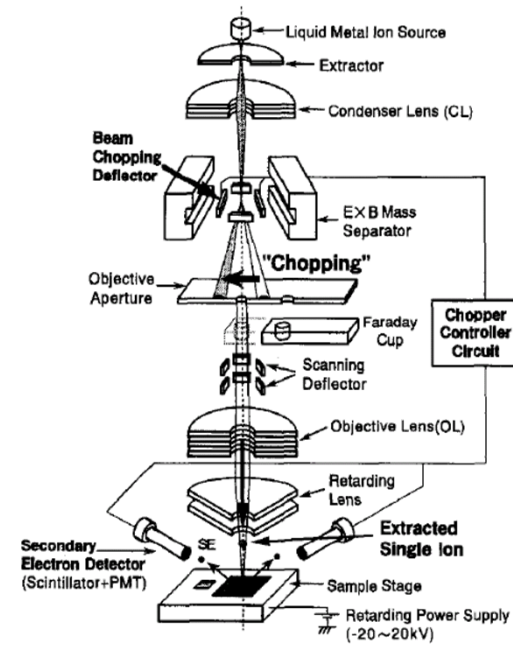


Use PMMA mask to define implant position



Deterministic control over:

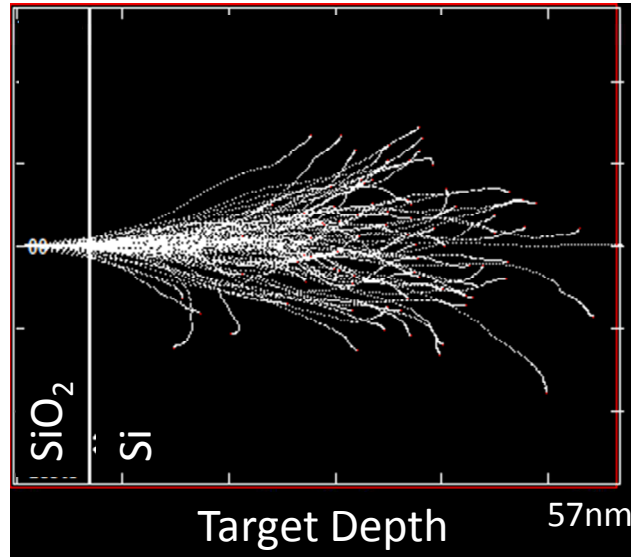
1. Placement of donors
2. Number of donors



Use a focused ion beam nano-implanter to limit implant to one lithographic site

# How we control donor location

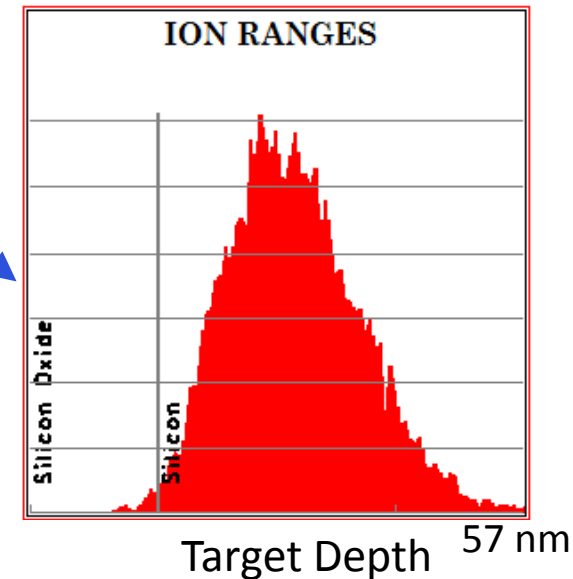
## Defining vertical position



SRIM simulation

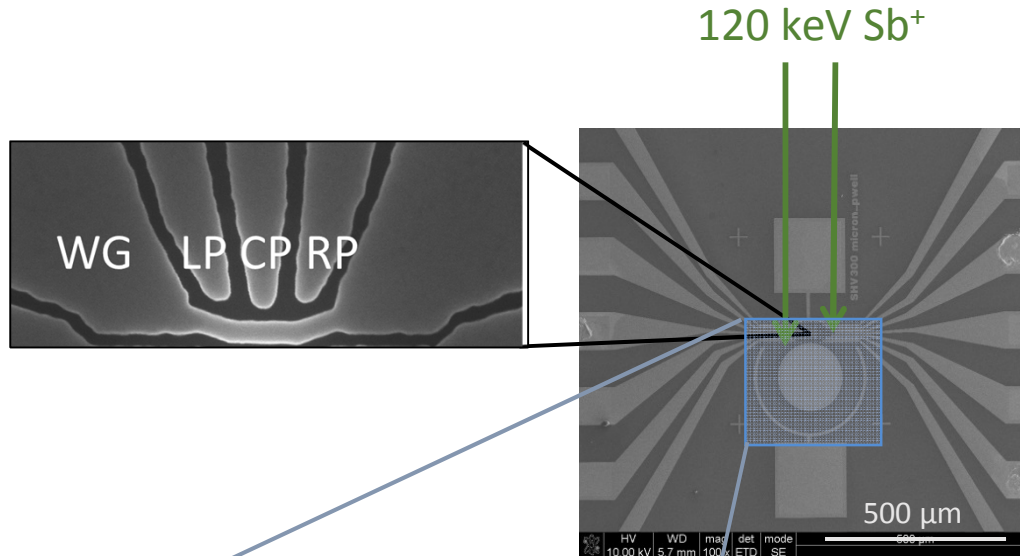
Deterministic control over:

1. Placement of donors ~15nm ✓
2. Number of donors



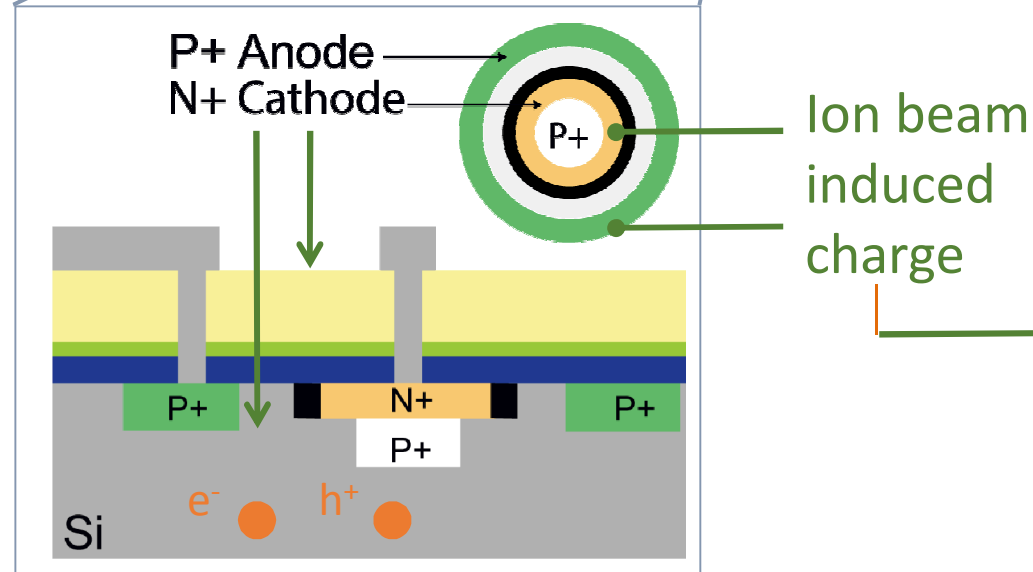
Low energy, heavy ion (120 keV Sb) used to minimize depth straggle

# How we control the number of donors



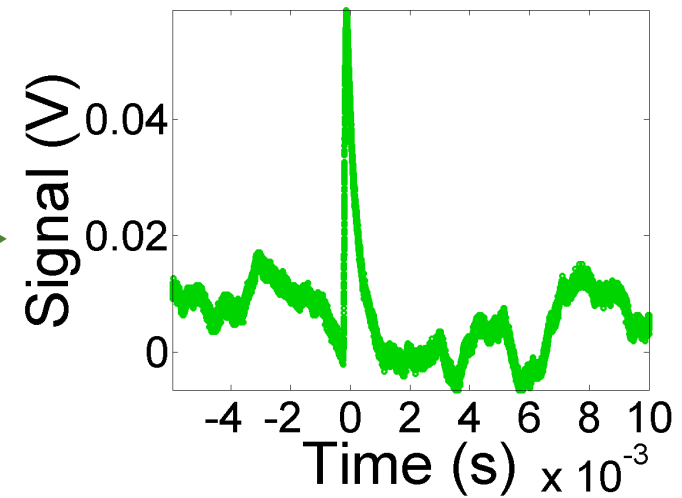
Deterministic control over:

1. Placement of donors ✓
2. Number of donors



Need to detect single ions

Response to <25> ions



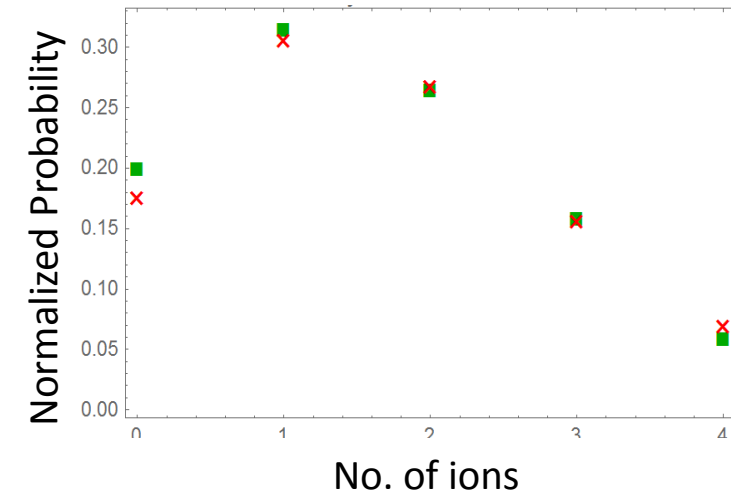
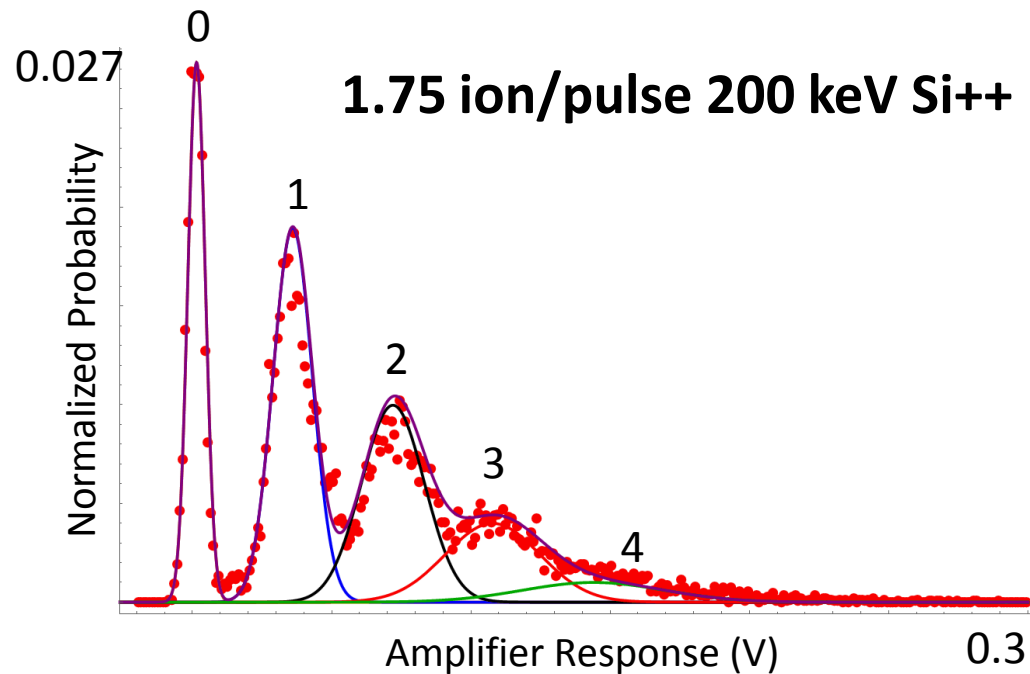
# Detecting a single ion

Recall

$$\langle \text{no. of ions} \rangle = \frac{\text{current} \times \text{time}}{\text{ionic charge}} = \text{Pulse length}$$

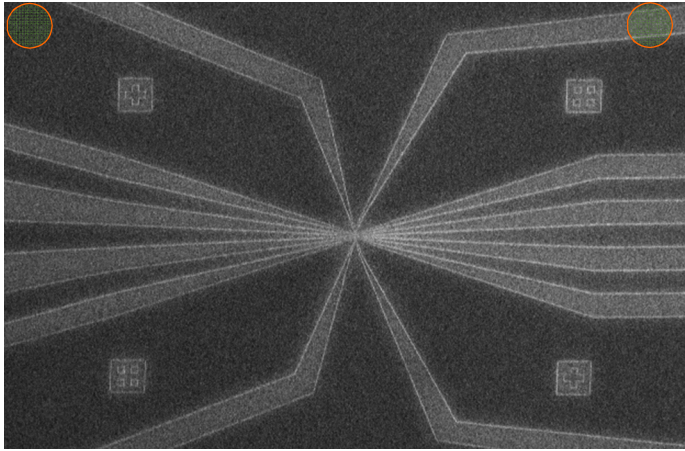
Poisson Statistics:

$$\text{actual no. of ions} = \langle \text{no. of ions} \rangle \pm \sqrt{\langle \text{no. of ions} \rangle}$$



# Detecting single ions

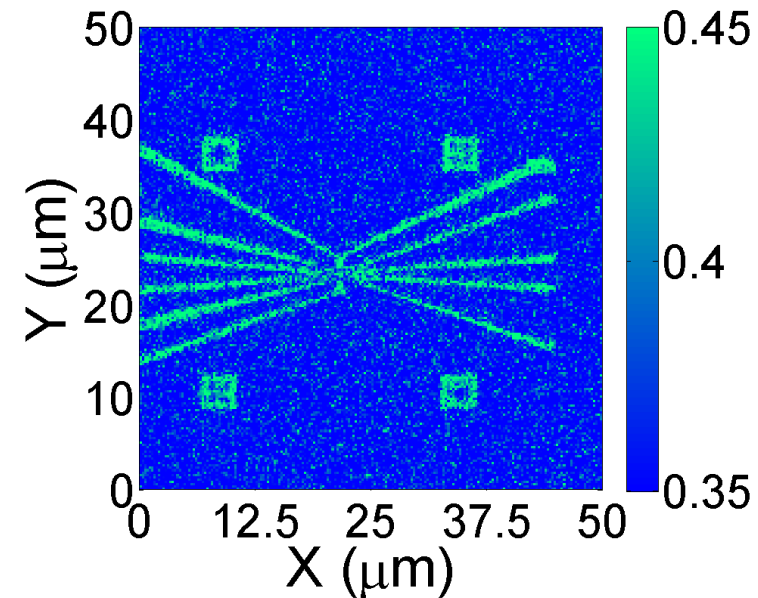
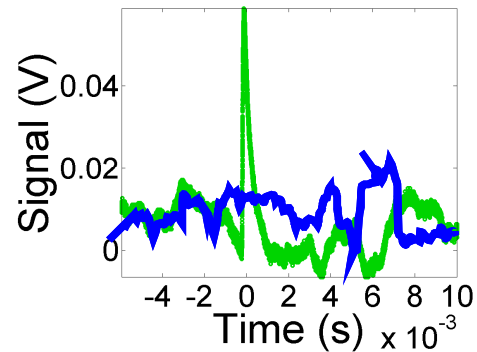
120 keV Sb<sup>+</sup>, <1> ion/pulse



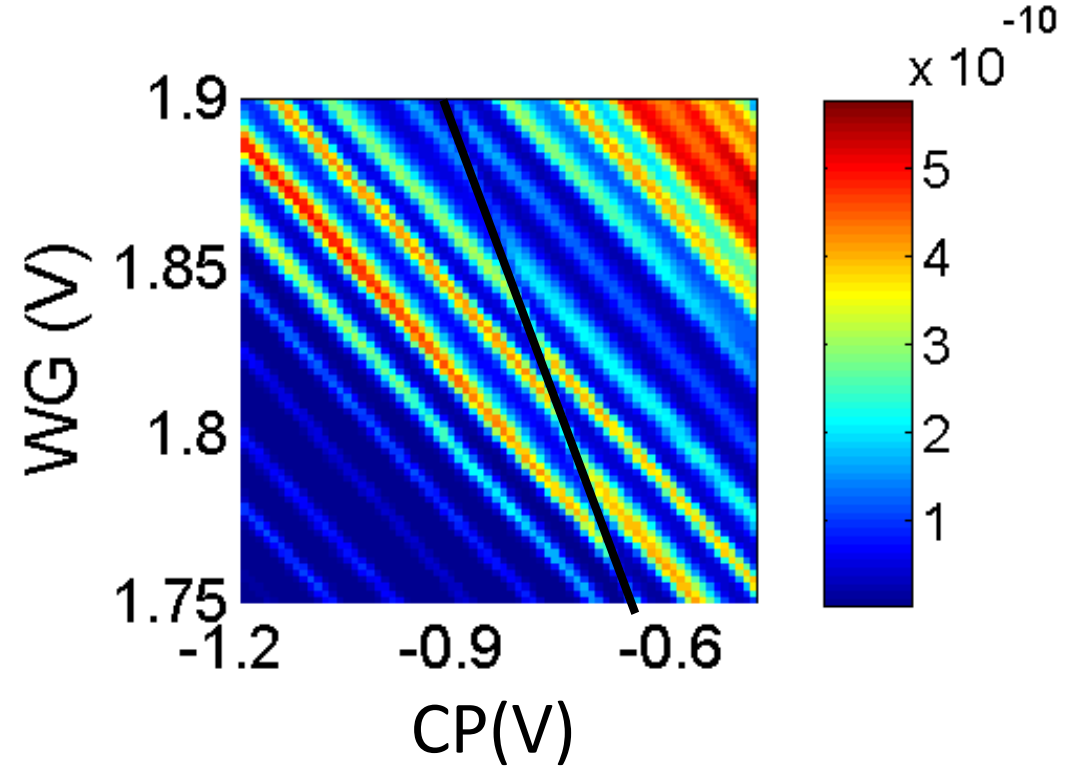
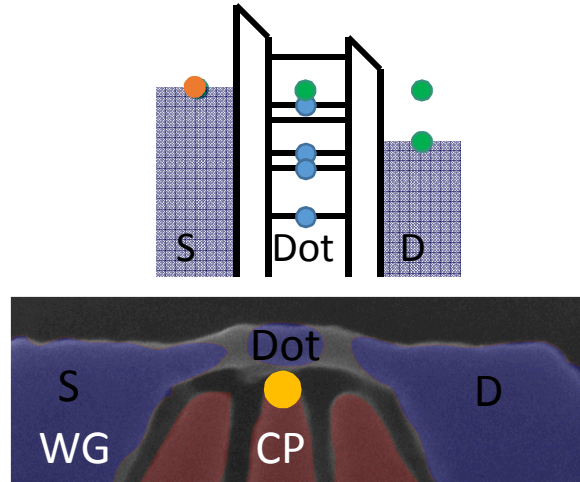
Deterministic control over:

1. Placement of donors ✓
2. **Number of donors** ✓

Recall

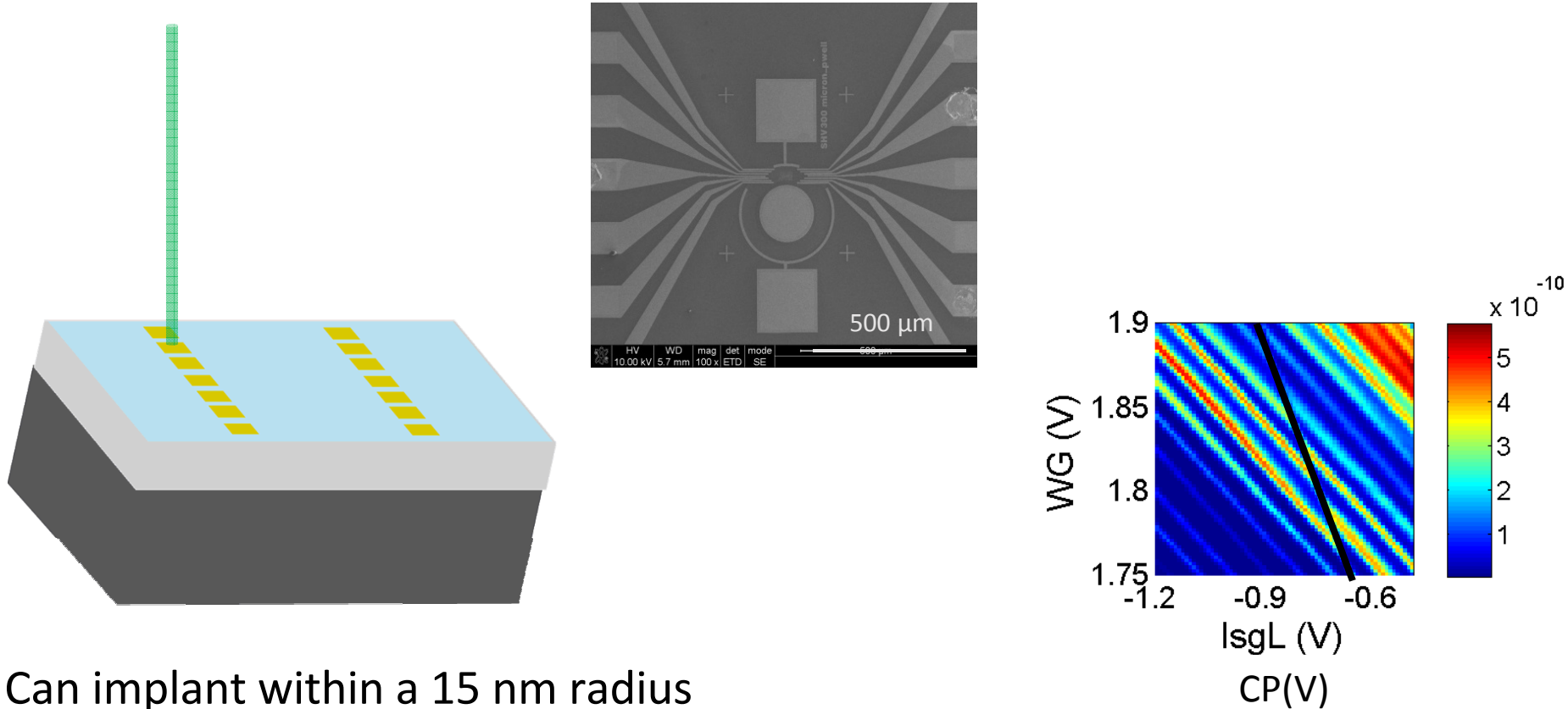


# Do the donors work? (Can the dot 'see' them)



In 6 implanted devices measured, 10-50% of implanted donors were seen

# In summary: what is the technology and what it can do



Can implant within a 15 nm radius

Can count single donors in situ

Can detect motion of the donor electron in transport

Immediate path forward to fabricating two qubit devices

APL **108**, 062101 (2016) – **Editor's pick** and in **AIP News** at the end of this month



Jose Pacheco C. Bureau-Oxton Daniel Perry



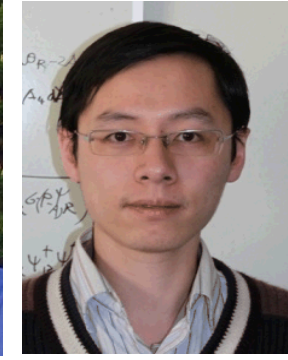
J. Dominguez Ron Manginell Greg Ten Eyck



Joel Wendt Tammy Pluym Dwight Luhman



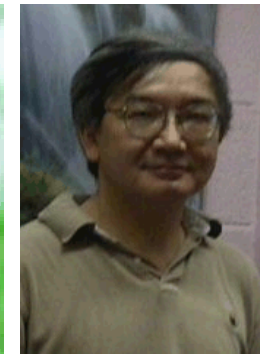
Ed Bielejec Mike Lilly Malcolm Carroll



Jian Wang Mingliang Tian Chaoxing Lu

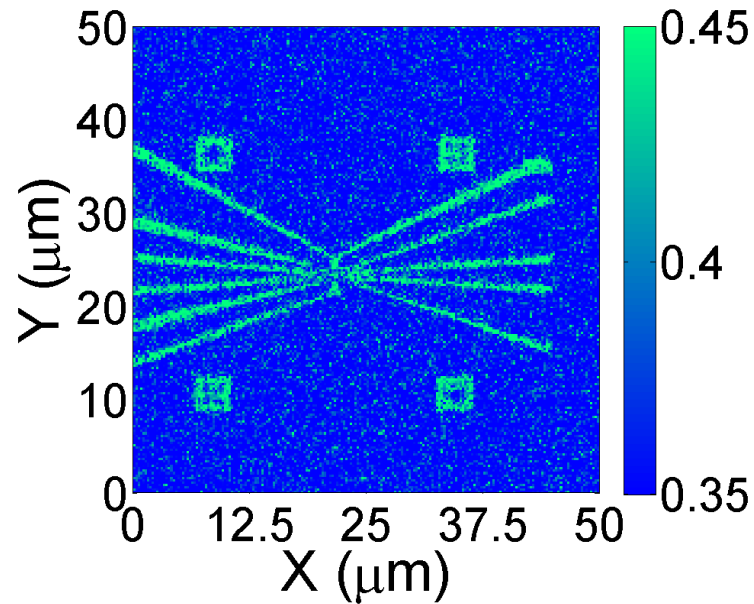


Jainendra Jain Nitin Samarth

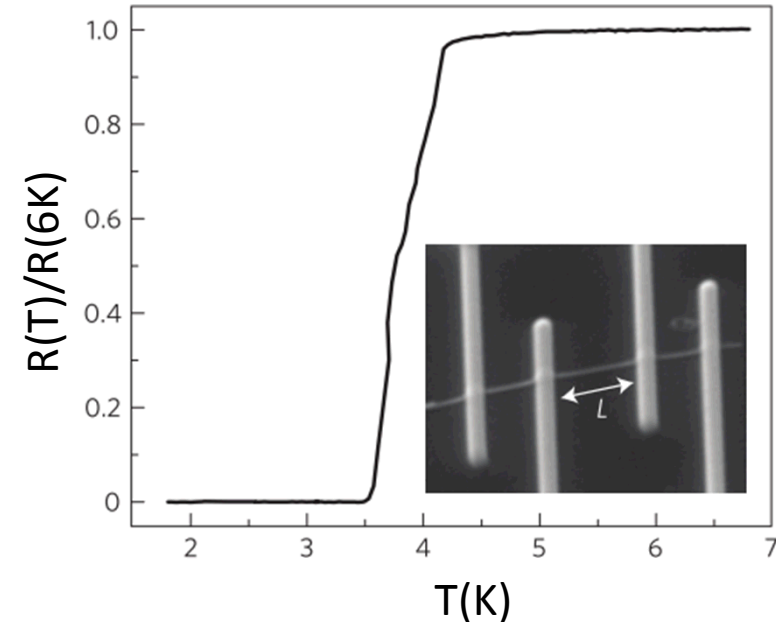


Tom Mallouk Moses Chan

# Overview – results, plans, Q&A



Development of a new technology  
enabling implant of a counted  
number of donors into a specific  
location – spin qubits



Discovery of a long-range  
superconducting proximity effect in  
ferromagnetic nanowires



Superspintronics

# Thank You