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Measurement of mesoscopic Si:P delta-doped devices fabricated by rapid STM hydrogen desorption lithography

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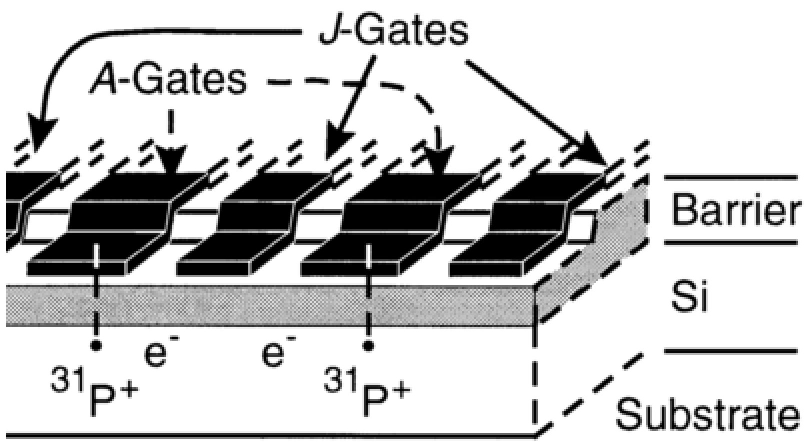
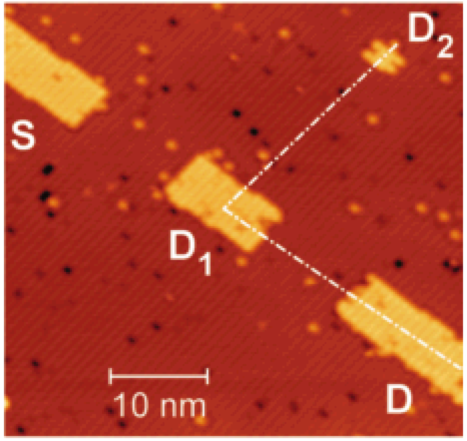
❖ Motivation

- Ultimate limits of scalability may soon be the end of Moore's Law
- Quantum computation schemes in Si are promising in terms of coherence and integration
- STM fabricated devices can achieve dimensions on the atomic scale:
  -Single atom transistor from UNSW

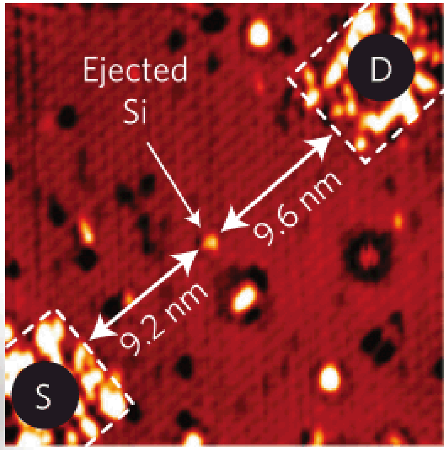
➢ Integration of STM devices is difficult due to large range of patterning scales necessary



Kane (1998)

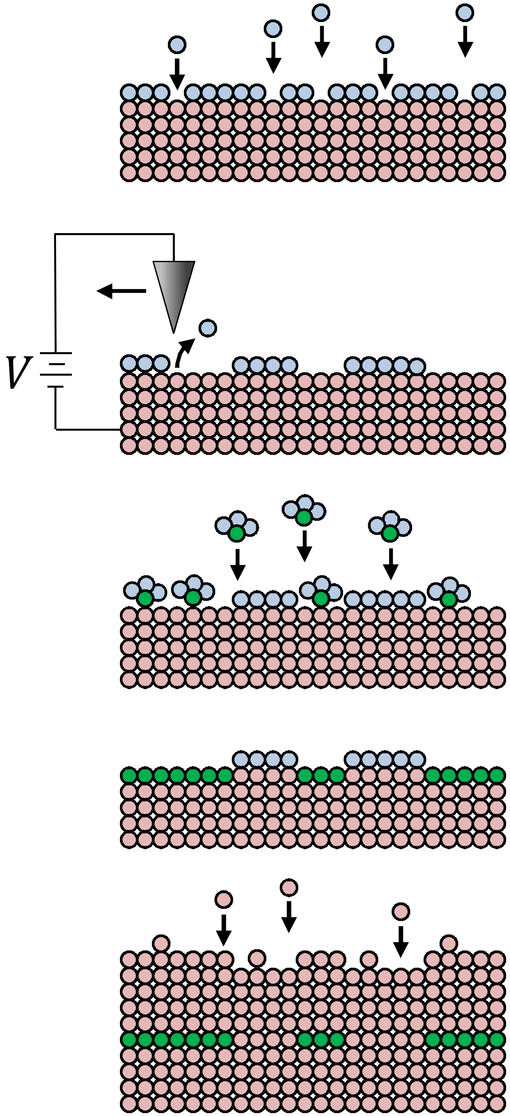


Mahapatra (2011)



Fuechsle(2012)

❖ STM H-desorption lithography



Passivate Si (100) with H

Selectively desorb H with atomic precision by STM

Introduce PH_3 gas

Incorporation anneal

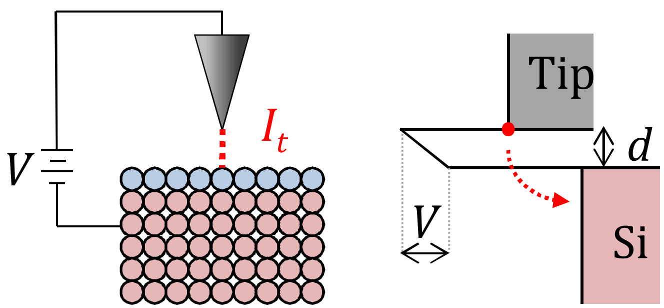
Grow epitaxial Si capping layer

Ruess (2004), Shen (2004)

- Highly doped delta-layer
  $n \approx 1\text{-}2\text{x}10^{14}\ \text{cm}^{-2}$
  $\mu \approx 50\text{-}100\ \text{cm}^2/\text{Vs}$
- Electrical connections to buried device is achieved by via interconnects and metallization
- Micron-sized contacting pads are a necessary component of the buried device

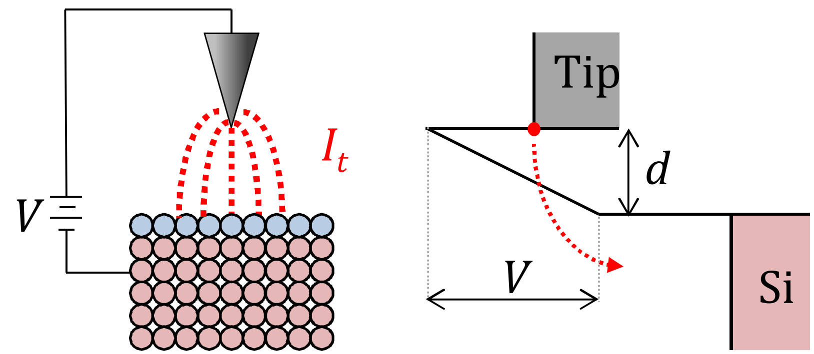
❖ Field emission H-desorption mode

Typical tunneling mode



- $d \approx 1$ nm
- $V \approx 4$ V
- $I_t \approx 1$ nA
- Single atom spot size
- Scan rate ≈ 50 nm/s

Field emission mode



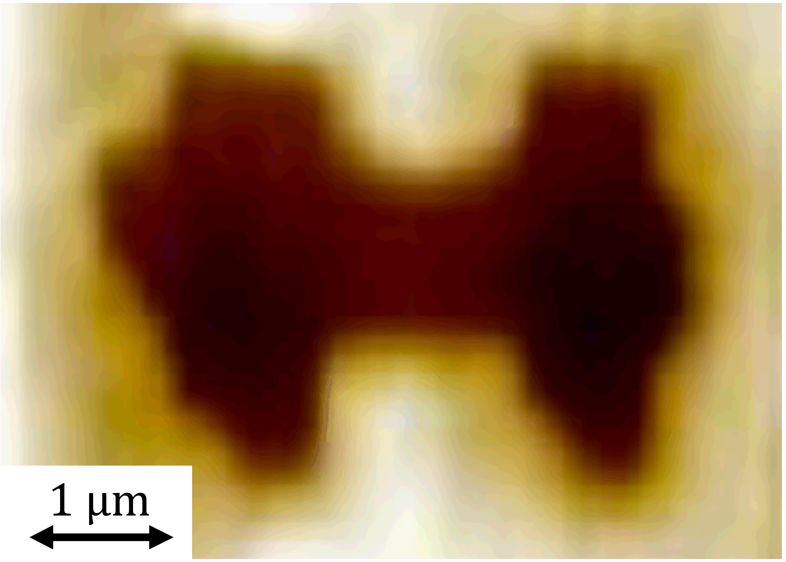
- $d > 10$ nm
- $V > 40$ V
- $I_t \approx 1$ nA
- Tunable spot size
- Scan rate ≈ 1 μm/s

- More than an order magnitude speed up of patterning time is possible

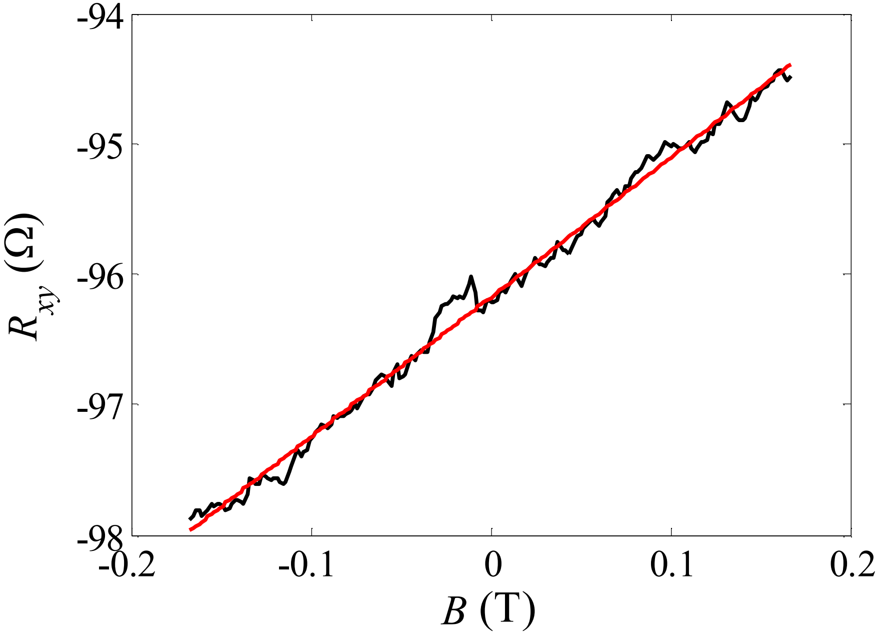
➢ Can field emission mode be used to pattern large contacting leads and pads?

➢ What size limit is imposed by patterning in field emission mode?

❖ Field emission patterned micron-sized Hall bar



SCM image of the buried device
(E. Bussman – Tuesday G24-05)



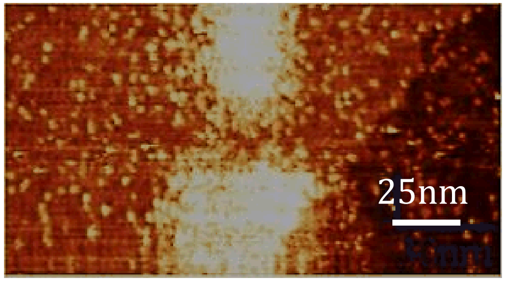
Hall and Van der Pauw measurements indicate:

$n \approx 6 \times 10^{13}$ cm^{-2} (expect 10-20 x 10^{13} cm^{-2})

$\mu \approx 50$ cm^2/Vs (expect 50-100 cm^2/Vs)

➢ Field emission STM patterning is viable for creating large conducting regions necessary for contact pads and device integration

❖ Field emission patterned tunnel gap device



STM image of H-desorbed region before P incorporation

- Top lead: single pass of tip in field emission mode
- Bottom lead: two passes of tip in field emission mode
- Spot size ~ 40 nm

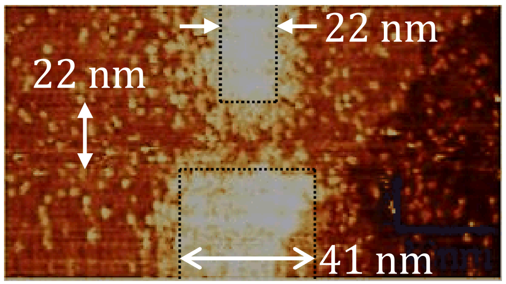
- Large spot size in the field emission mode creates an unsharp H mask
  - ➢ How small of a feature can be accurately written in field emission mode?

➢ Does a barrier exist between the leads?

➢ Is the tunnel gap clean?

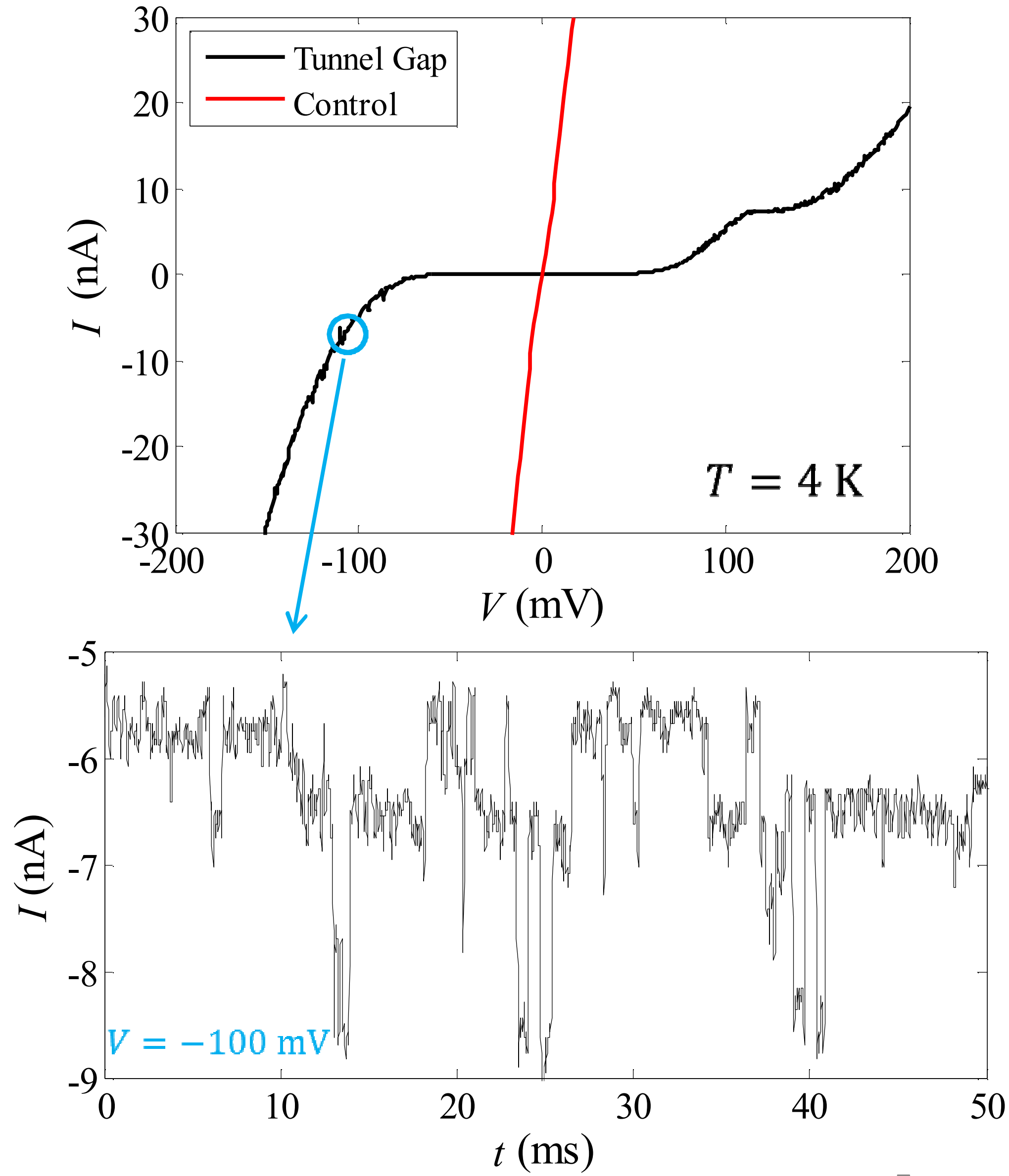
➢ Where do the P dopants incorporate?

❖ Field emission patterned tunnel gap device



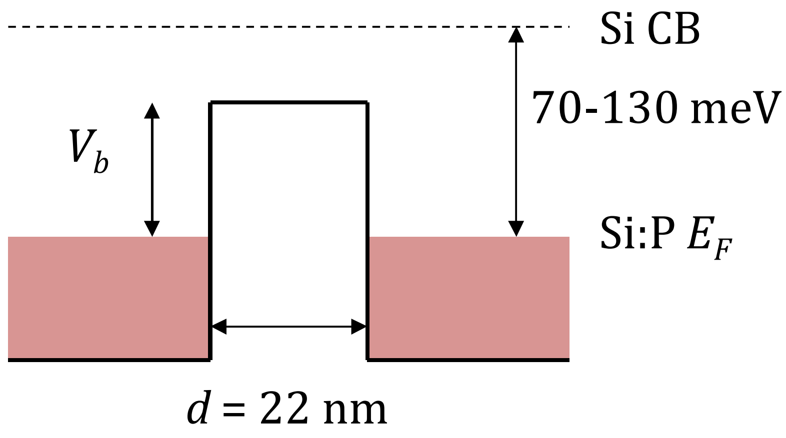
STM image of H-desorbed region before P incorporation

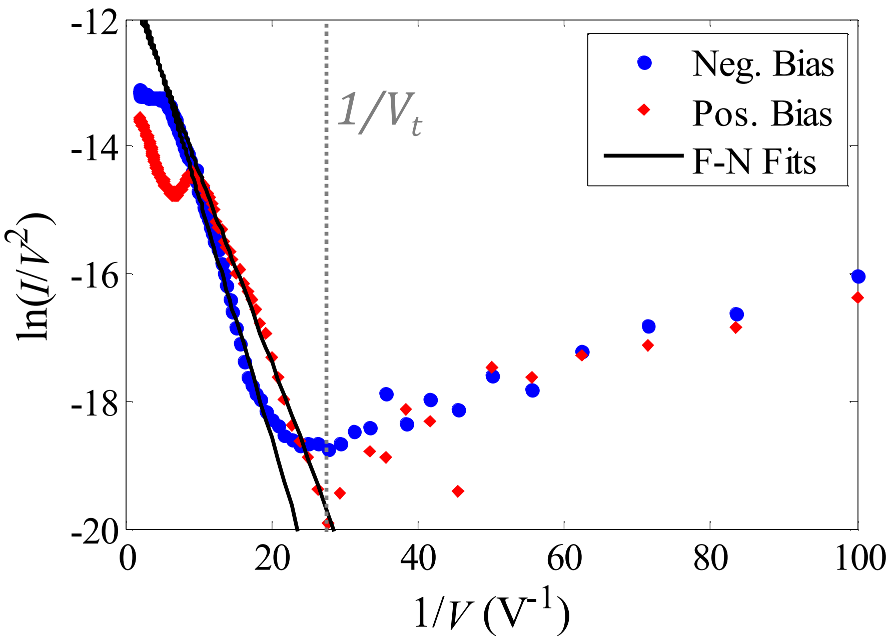
- Tunnel gap device displays a robust barrier for $|V| < 50$ mV
- Second plateau may represent a secondary conduction path through a donor island
- Random telegraph noise shows ~4 metastable levels indicating few donor islands are in/near the tunnel gap



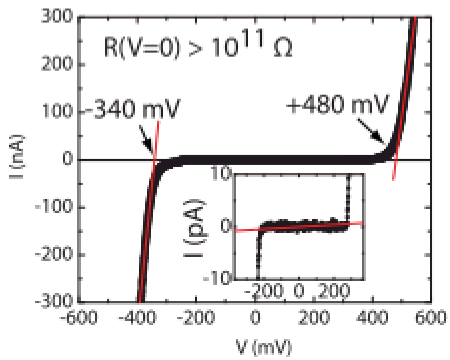
❖ Tunnel barrier fits

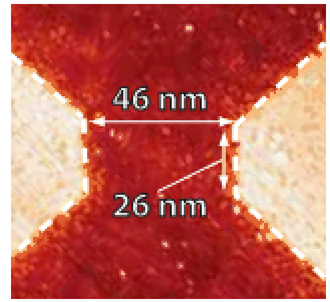
- Fowler-Nordheim Plot
  - $V_b \approx V_t = 35$ mV
- $\ln\left(\frac{I}{V^2}\right) \propto -\frac{4d\sqrt{2m^* V_b^3}}{3\hbar q}\left(\frac{1}{V}\right)$
  - $V_b = 27 \pm 2$ mV
- Actual barrier is parabolic, so F-N gives a low estimate on V_b
- Calculated V_b consistent with the bound placed by the Si CB



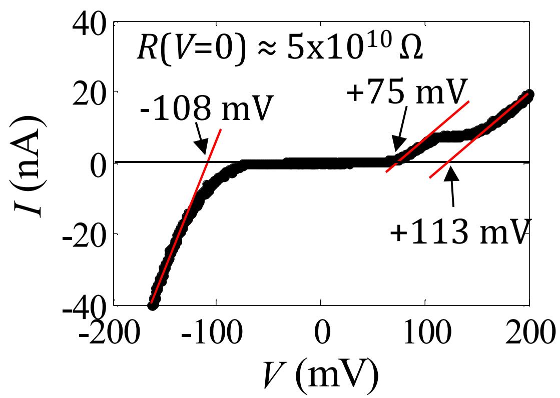


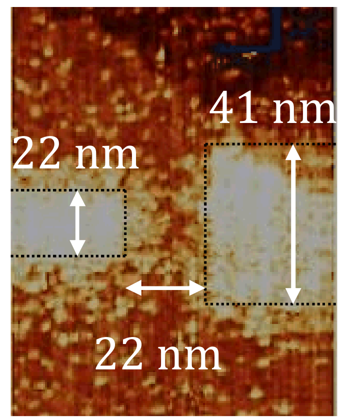
❖ Comparison to tunnel mode devices



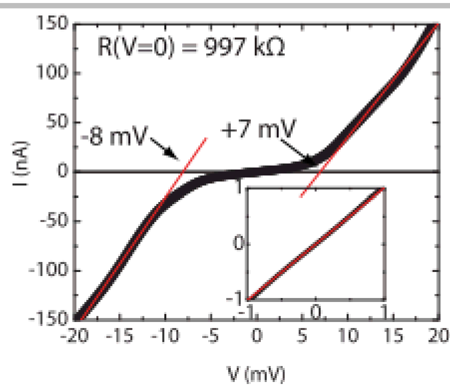


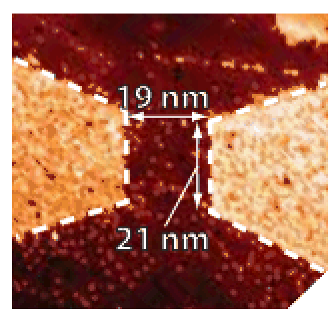
UNSW (2011)
-tunnel mode





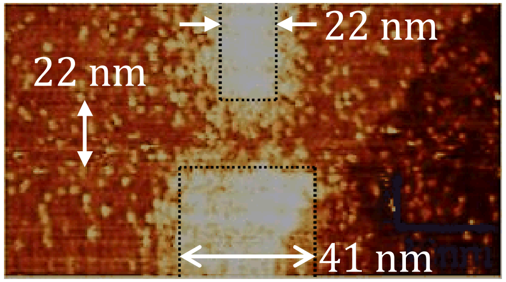
This work
-field emission mode



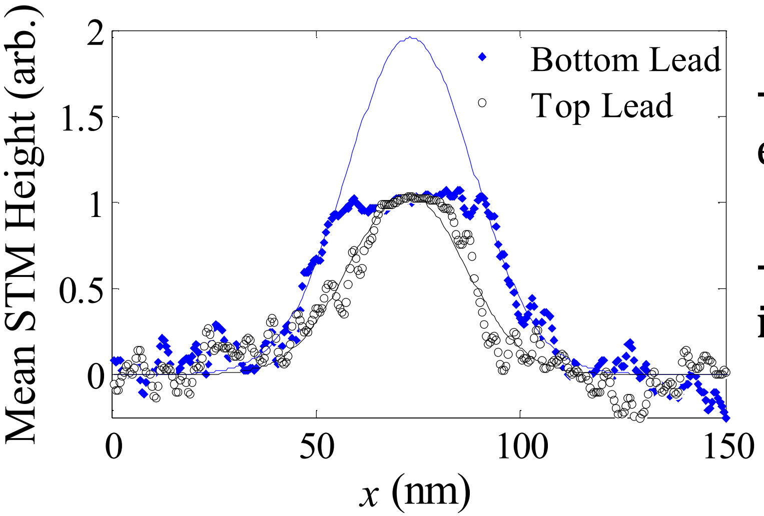


UNSW (2011)
-tunnel mode

❖ Tunnel gap device electrical dimensions

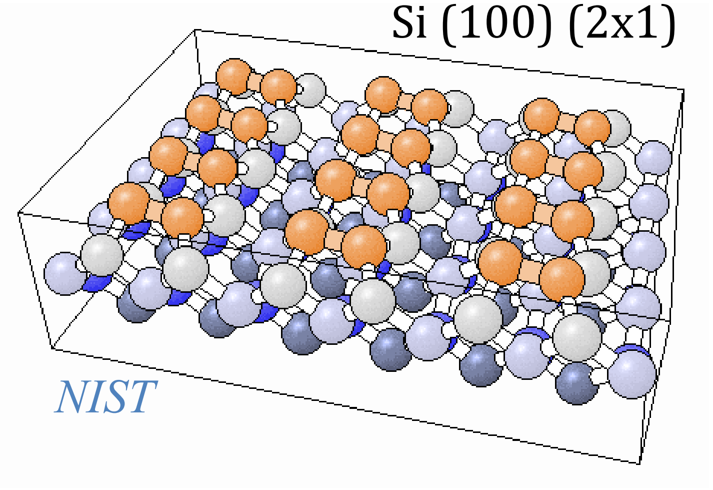


STM image of H-desorbed region before P incorporation



-Bottom lead was exposed twice

-Gaussian fits ignore plateaus

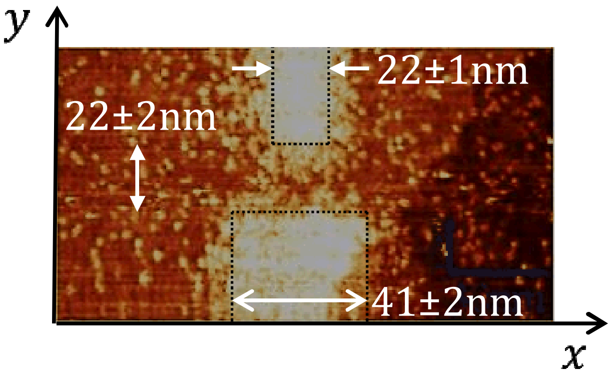


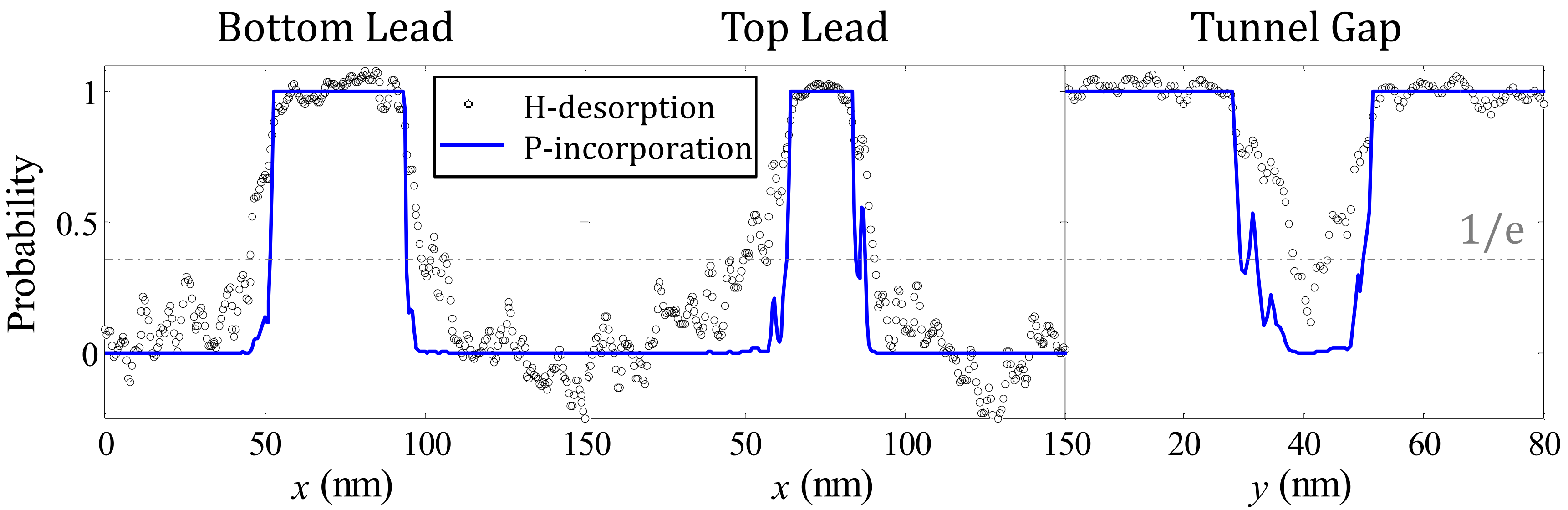
- Three adjacent Si dimers must be available for P to incorporate
- Given P_{des} is the probability that H is desorbed from the surface (P_{des}), the probability of P incorporating (P_{inc}) is:

$$P_{inc} < 0.7(P_{des})^6 + 0.78(P_{des})^8 + 0.85(P_{des})^{10} + (P_{des})^{12} + \cdots$$

Fuechsle (2012)

❖ Tunnel gap device electrical dimensions



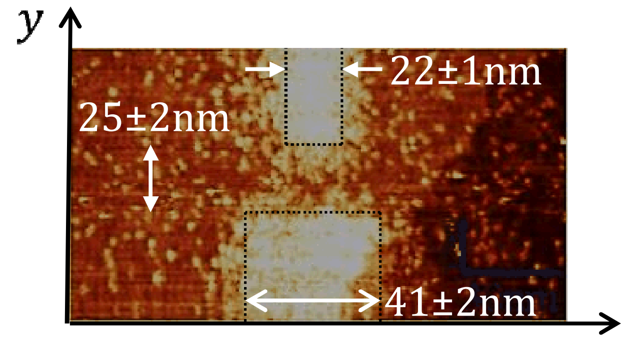


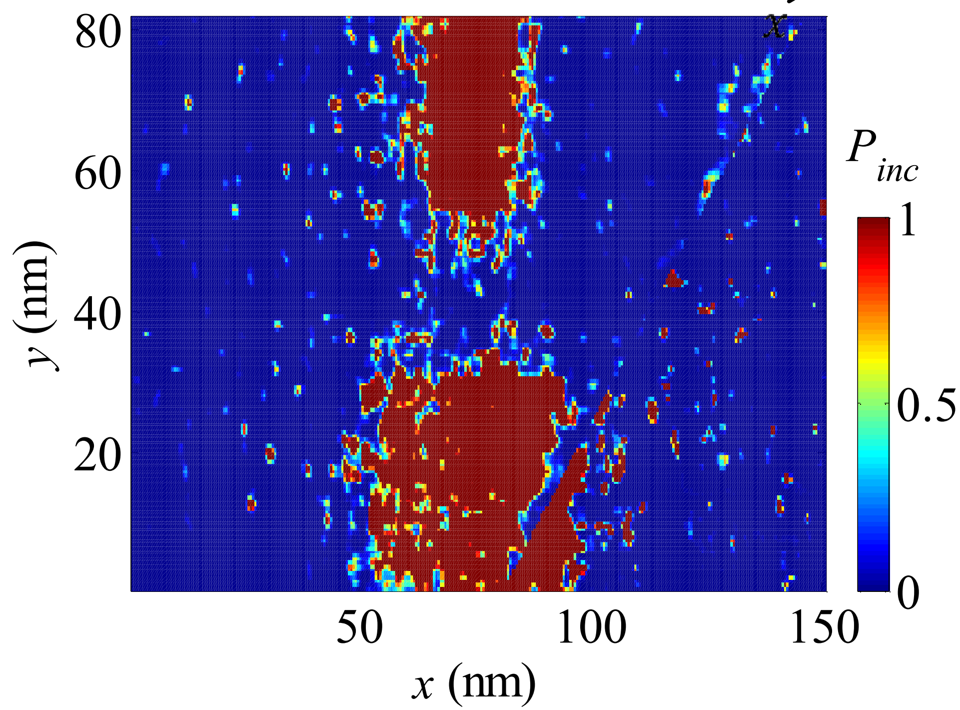
$$P_{inc} < 0.7(P_{des})^6 + 0.78(P_{des})^8 + 0.85(P_{des})^{10} + (P_{des})^{12} + \cdots$$

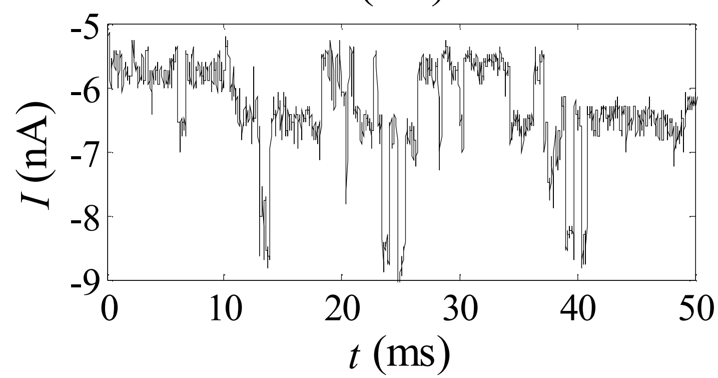
Fuechsle (2012)

❖ Dopant profile

- Bohr radius of a P dopant in Si
  $a_B \approx 2.5$ nm
  - ➢ Most donor islands are electrically connected to leads
  - ➢ ~5 isolated donor islands are present in the gap
- Consistent with the ~4 metastable states in the random telegraph signal observed







❖ Conclusions

We introduce a method of H-desorption lithography by STM in a field emission mode

- Order of magnitude increase in patterning speed over conventional tunnel mode
- Successful P delta-layer incorporation on large scale areas
- 22 nm tunnel gap written with a 40 nm spot size shows comparable tunnel barrier characteristics to atomically precisely patterned tunnel mode devices
- P incorporation chemistry creates nearly atomically abrupt defined devices with few delocalized donor clusters

The field emission mode is ideal for patterning large contacting areas, but can also be used for devices on the nanometer scale

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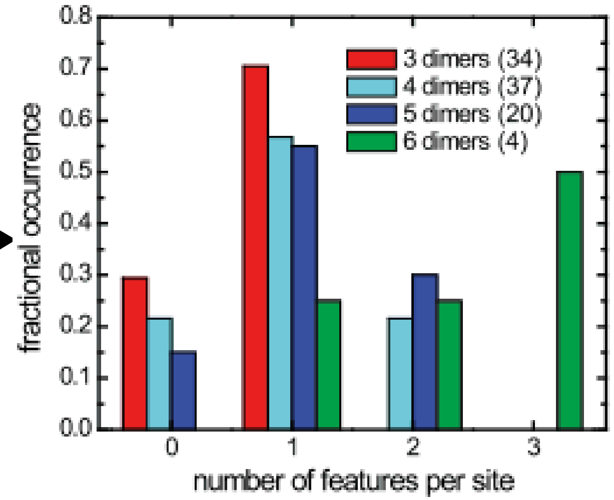
❖ P incorporation probability assumptions

- UNSW studied the probability of incorporating a P atom with varying the number of H-desorbed dimers

- Assume the 2 H desorbed from Si dimer have equal probability of being desorbed

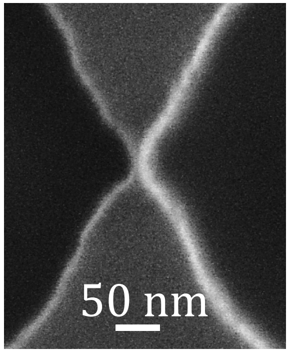
- Neglect length scales required for 3 open dimers to exist

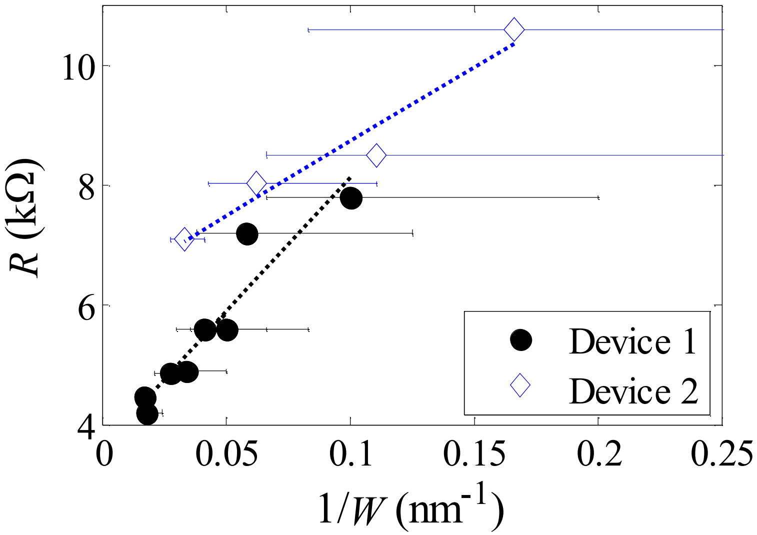


Fuechsle (2012)

$$P_{inc} < 0.7(P_{des})^6 + 0.78(P_{des})^8 + 0.85(P_{des})^{10} + (P_{des})^{12} + \cdots$$

❖ EBL/etch defined Si:P delta layer nano-constrictions





EBL patterned constrictions in similar Si:P delta layers indicate leads of 6 nm in width are ohmic