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Thermal activation of low-density Ga implanted in Ge

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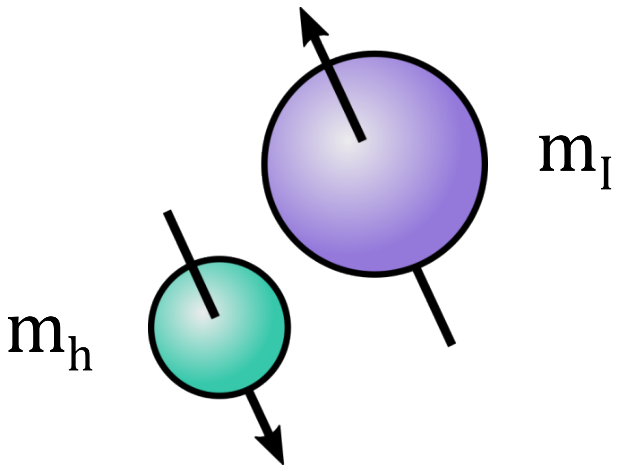

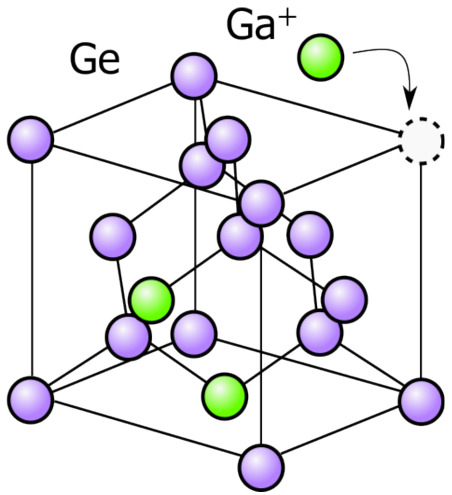

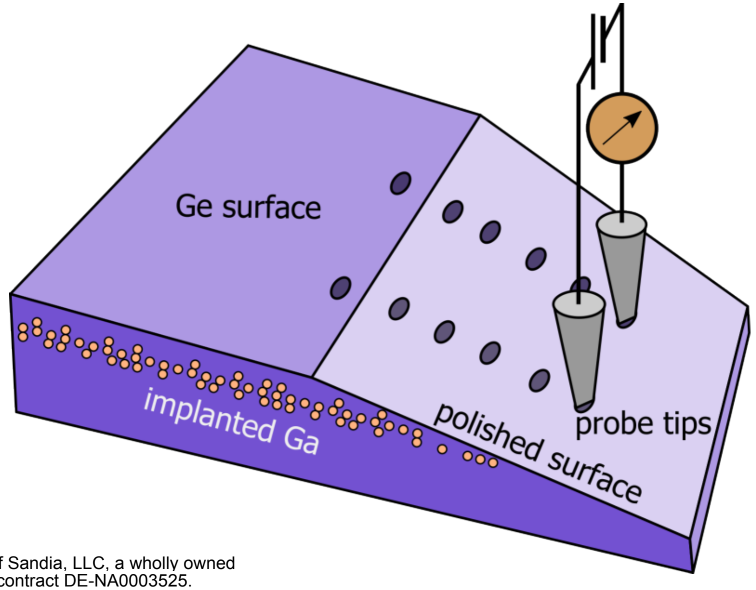

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Outline

- Background: Nuclear spins as qubits
- The experiment
- Results & discussion

Nuclear spin qubits in silicon and germanium

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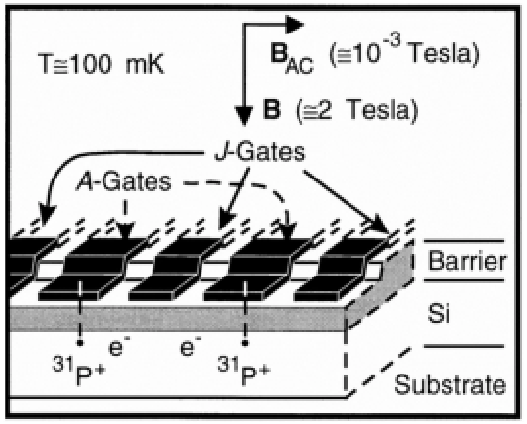
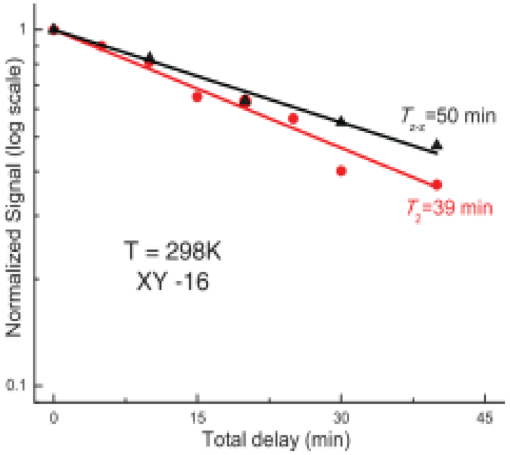
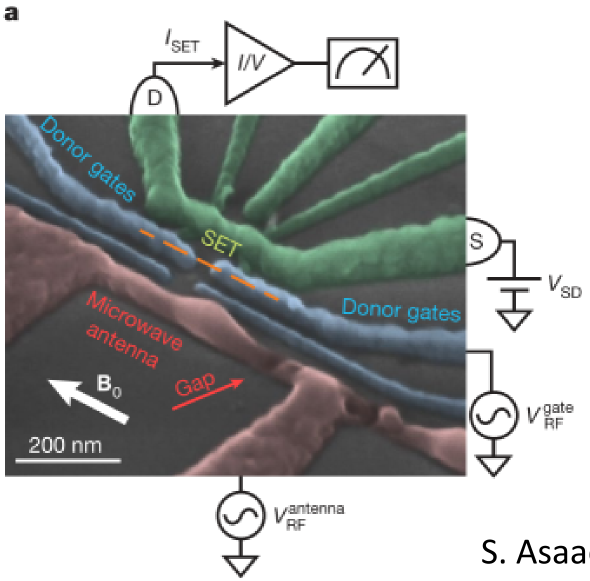
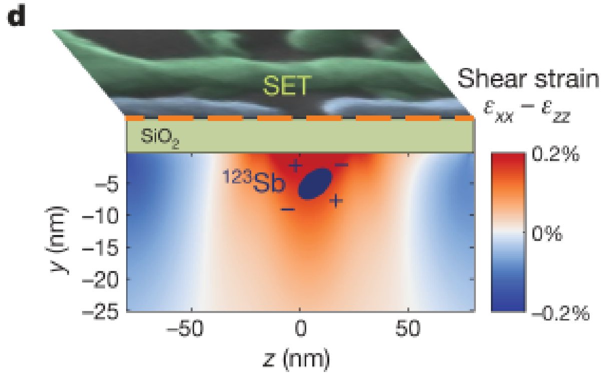


B. Kane *Nature* 393 (1998) 133-137

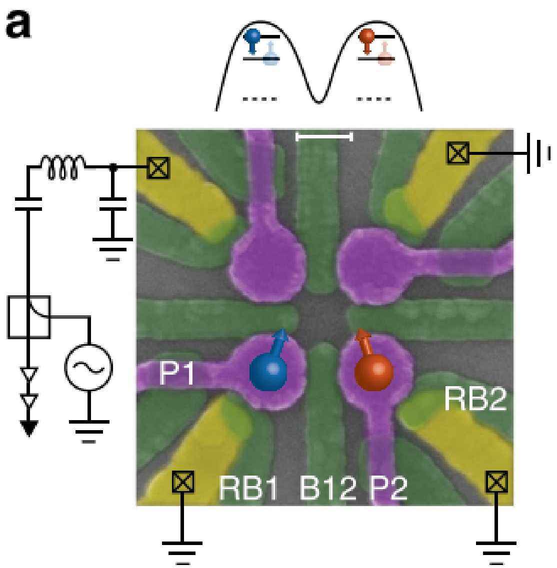


K. Saeedi et al. *Science* 330 (2013) 830-833

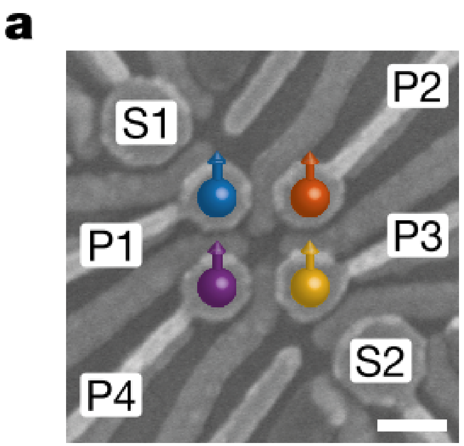




S. Asaad et al. *Nature* 579 (2020) 205-209



N. Hendrickx et al, *Nat. Comms* 11 (2020) 3478



N. Hendrickx et al, *Nature* 591 (2021) 580-585

✓ Scalable ✓ Long coherence times	Si
✓ High mobility (~10^6 $cm^2/V\ s$) ✓ Large spin-orbit coupling ✓ Tunable g-factor	Ge

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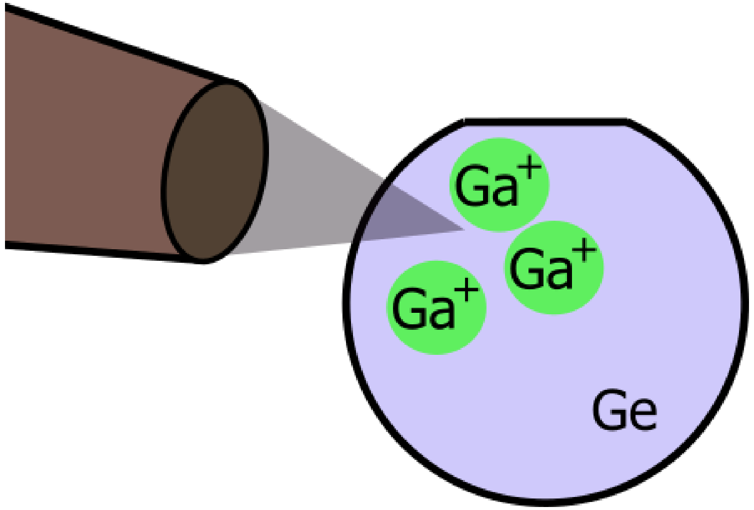
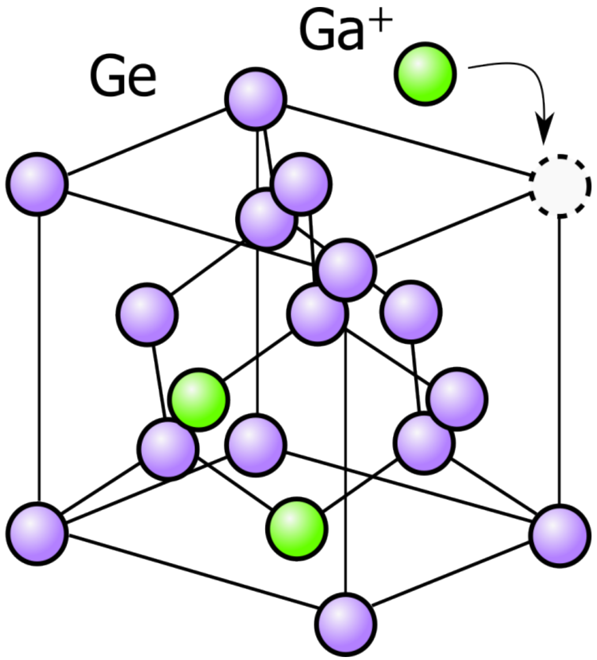
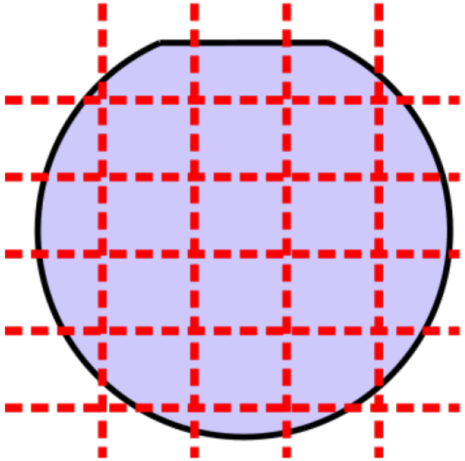
Rapid thermal annealing of implanted dopants

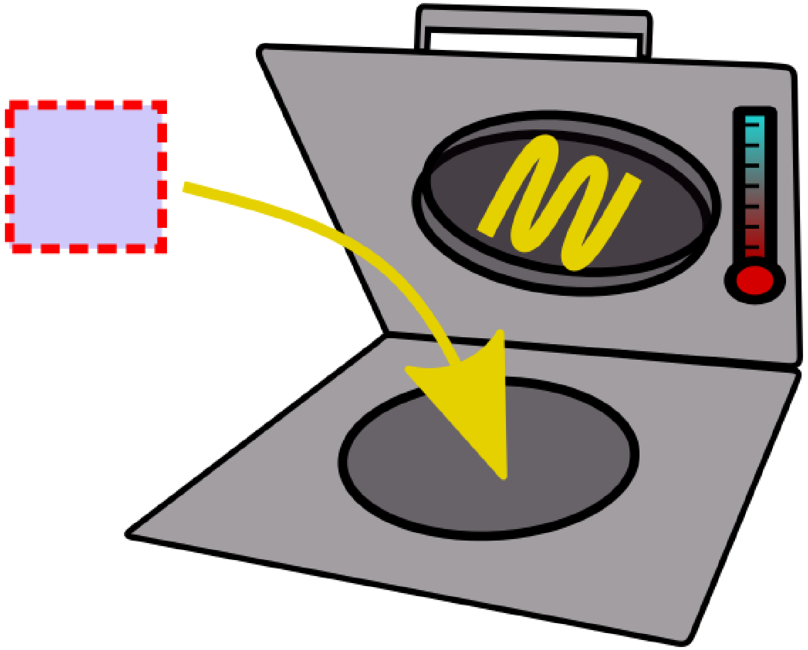


Focused ion beam implantation

Energy = 175 keV
Fluences = $6 \times 10^{10} – 6 \times 10^{12}$ cm^{-2}







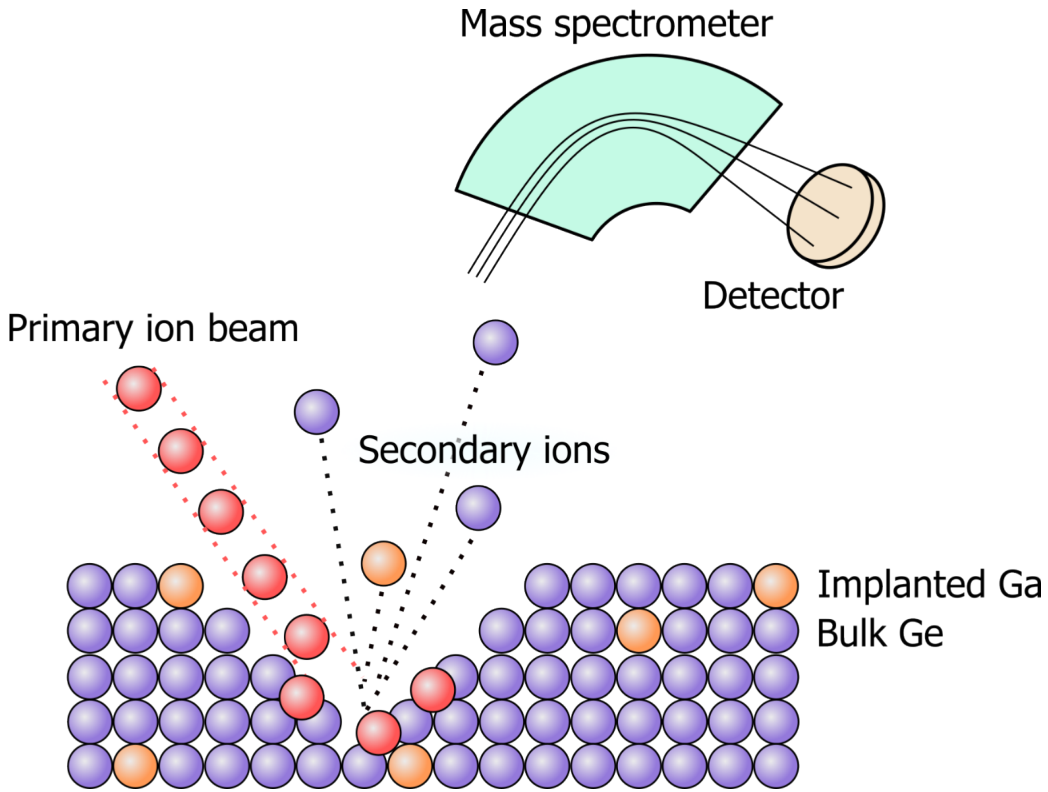
Rapid thermal annealing

Temperatures = 200 – 850 ^{o}C

Allows dopants to move onto substitutional sites and become electrically active

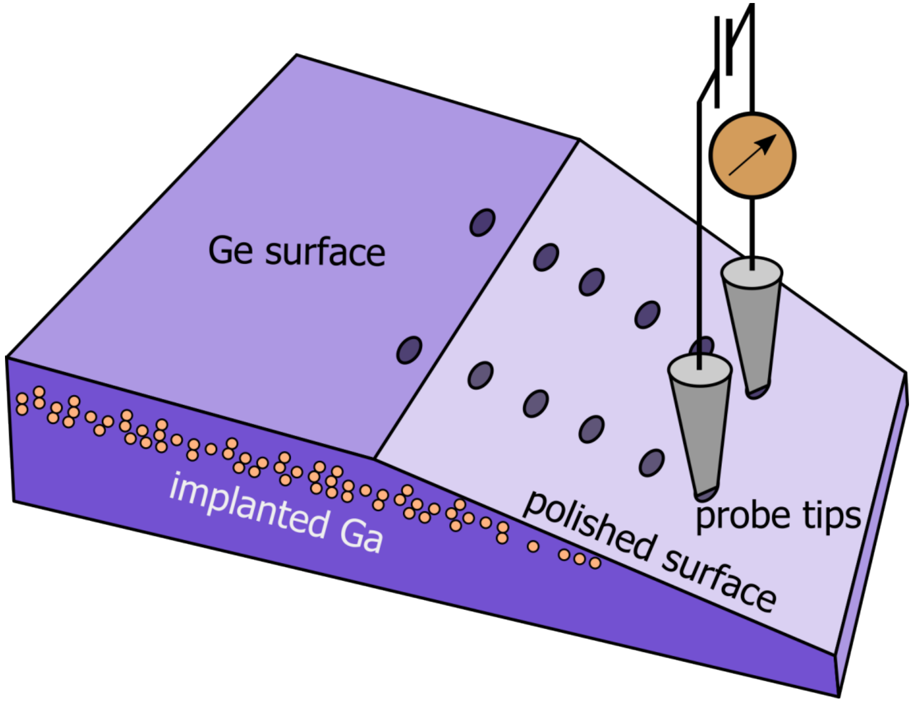
Secondary ion mass spectrometry (SIMS) and spreading resistance profiling (SRP) analysis

SIMS



Total number of Ga ions

SRP



Total charge carrier density

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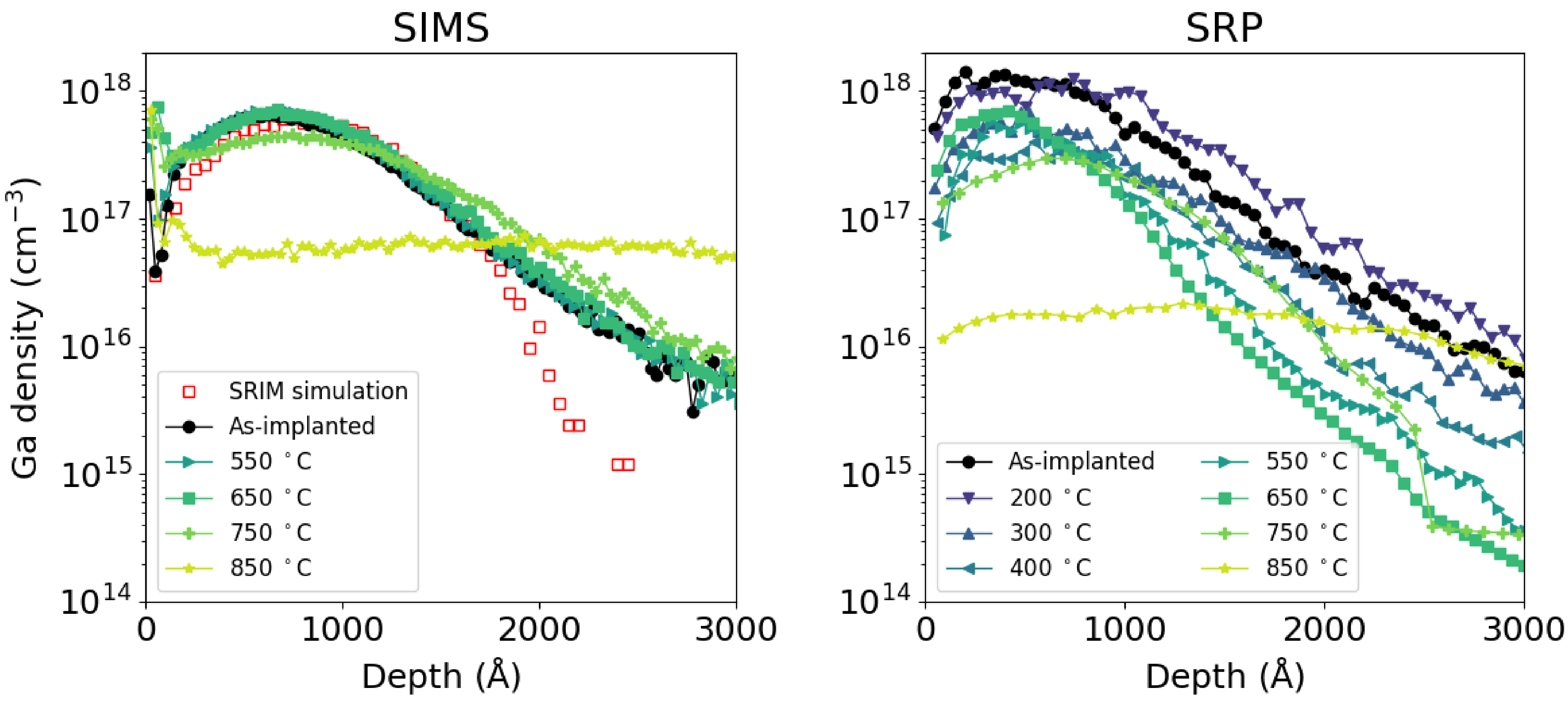
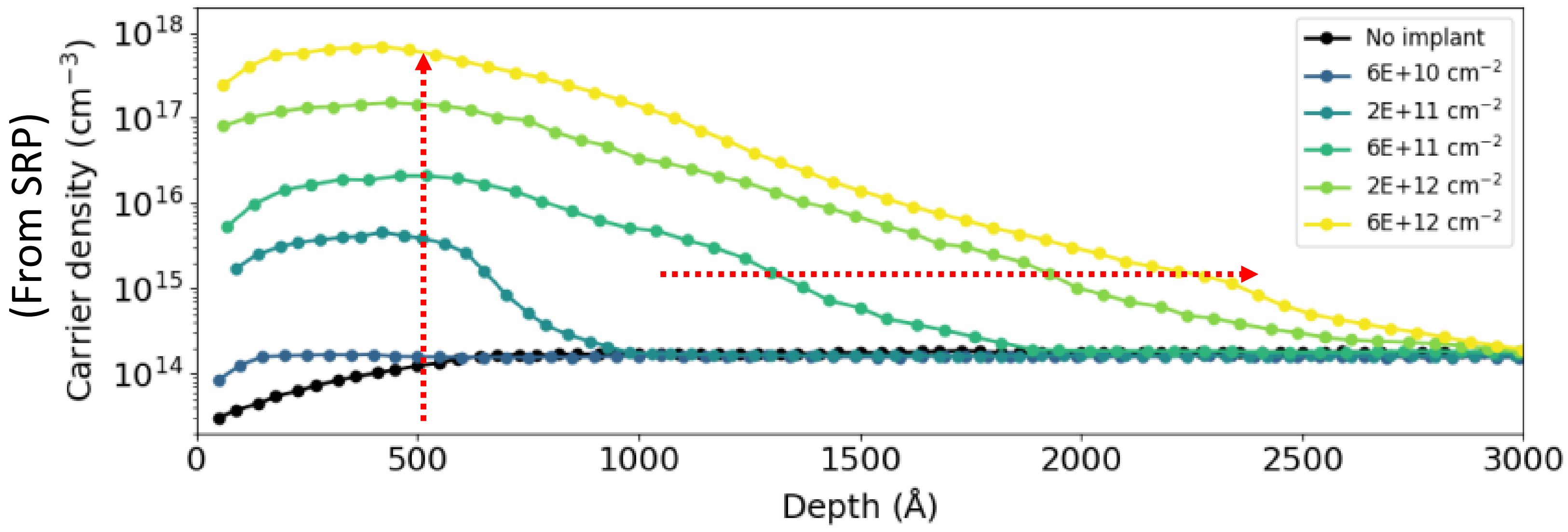
Implanted dopant distribution broadens at high anneal temperatures

Implant fluence = $6x10^{12}$ cm^{-2}



Implant fluence extends carrier density profile but maintains peak depth

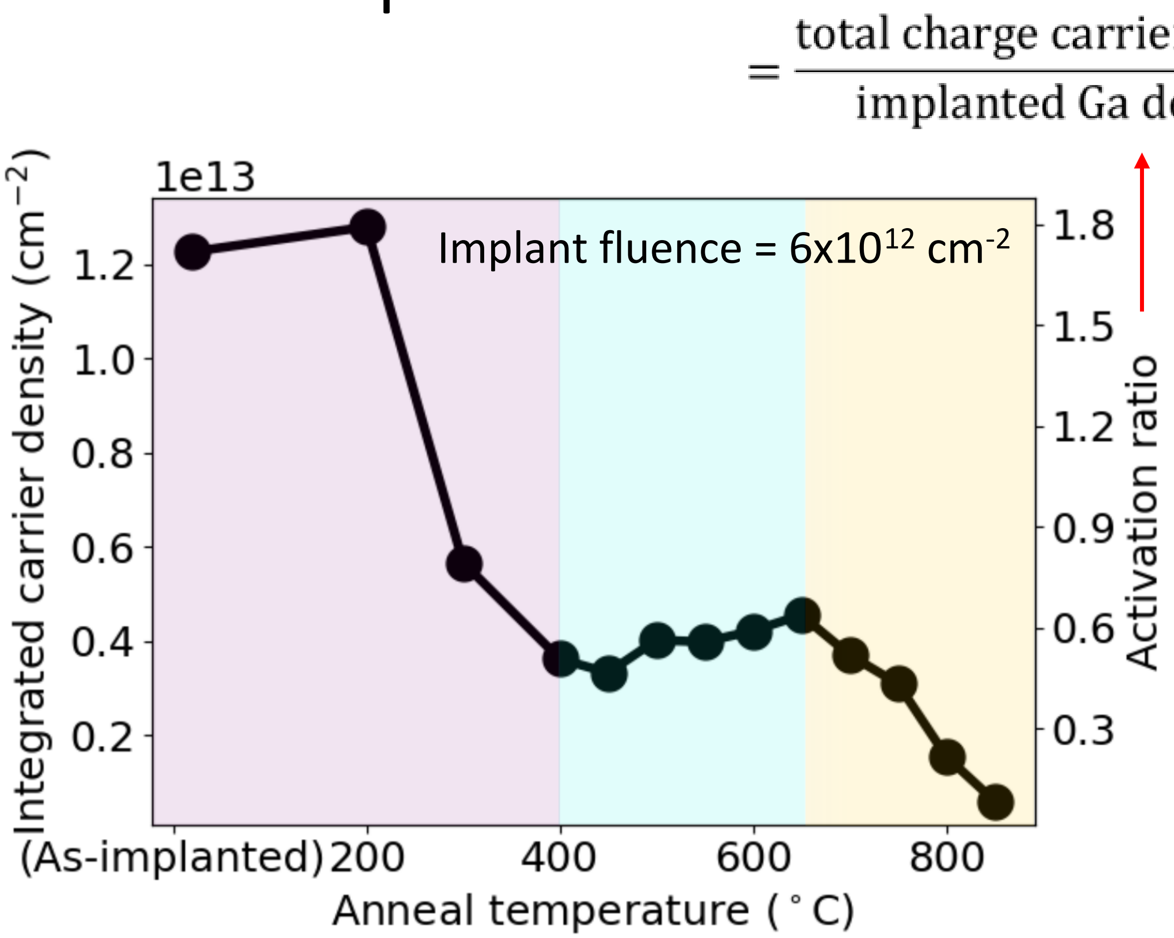
Anneal temperature = 650 ^{o}C

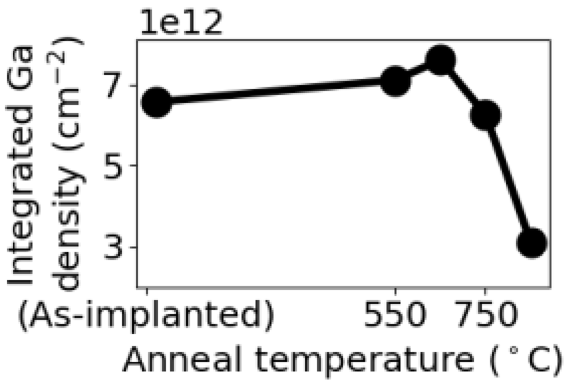


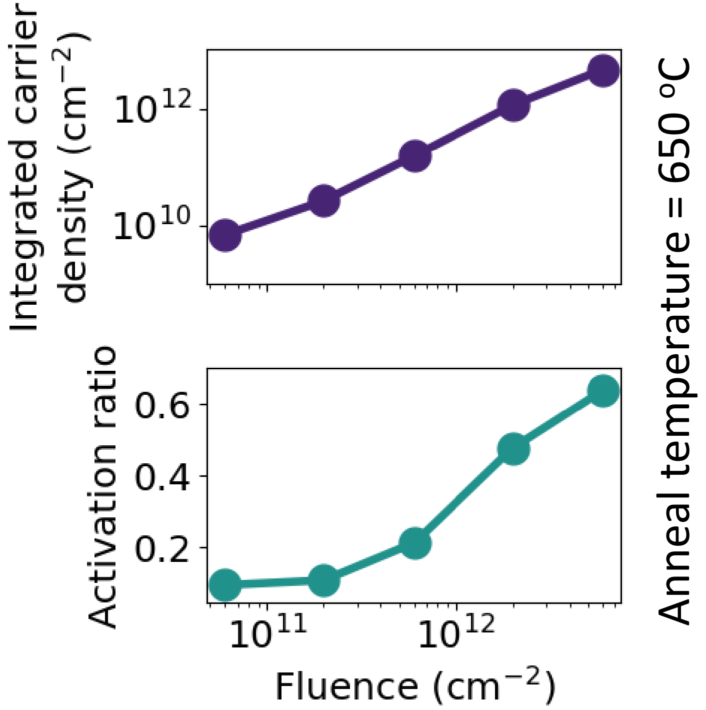
Peak carrier density near 500 Å depth

Carriers reaching into germanium surface

Thermal annealing drives electrical activation of implanted dopants



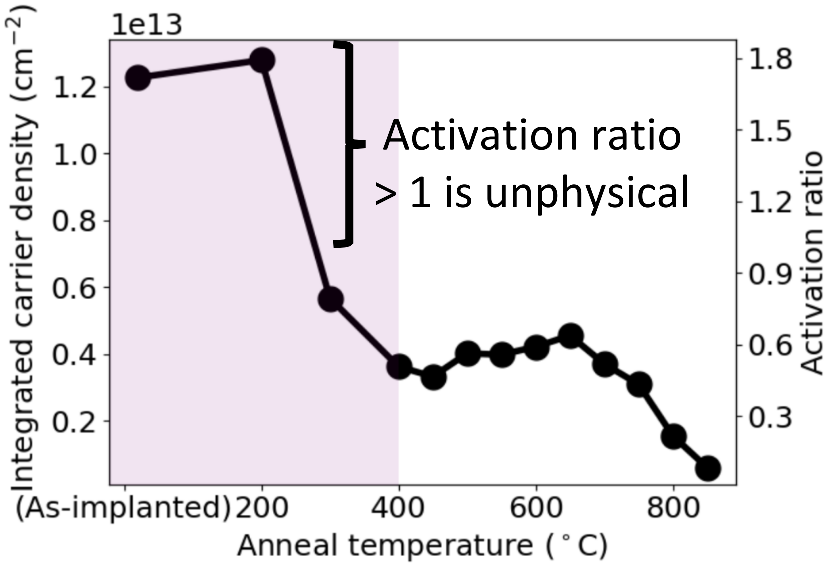




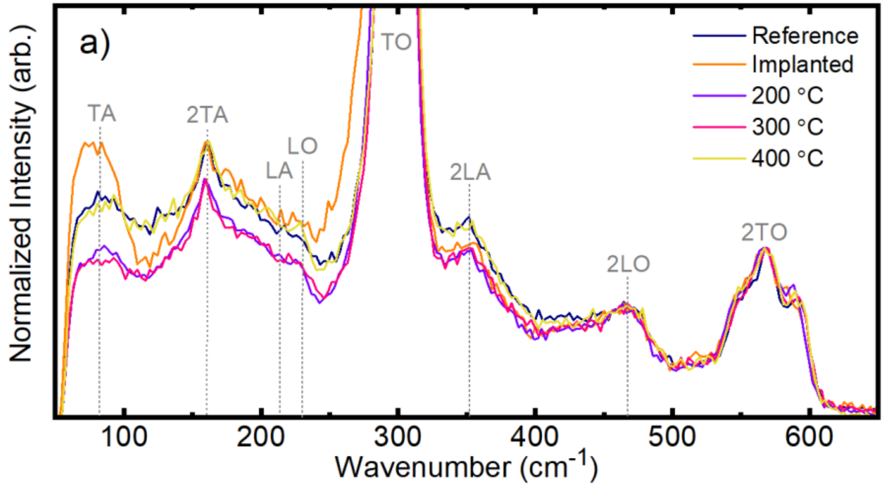
i) T < 400 °C **ii) 400 °C < T < 650 °C** **iii) T > 650 °C**

Implant-induced defects are excess charge carriers

Raman spectroscopy probes the strain-induced phonon mode shift



i) T < 400 °C

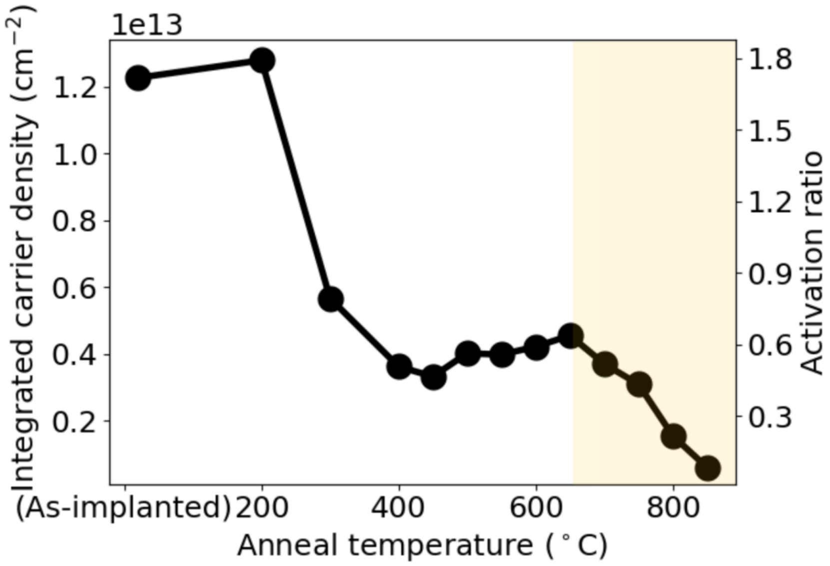


- Defect charge carriers contribute to unphysical activation ratio

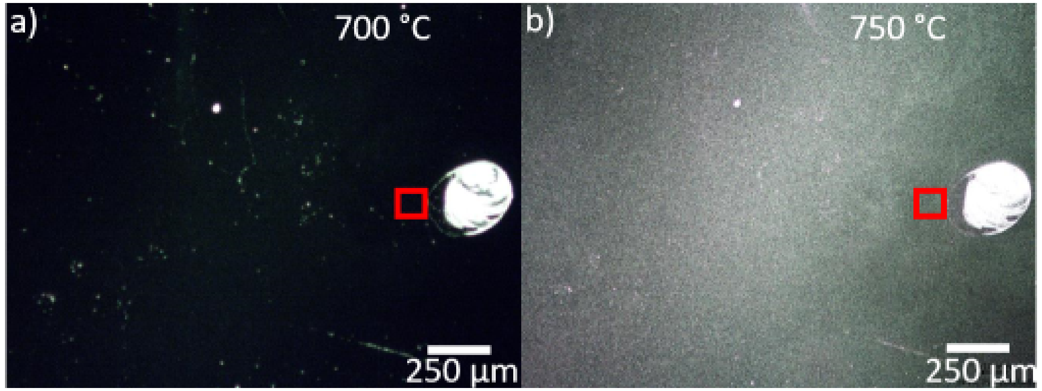
- Thermal annealing heals implant damage

Loss of dopants increases with high anneal temperatures

Atomic force microscopy characterizes surface roughening as dopants diffuse

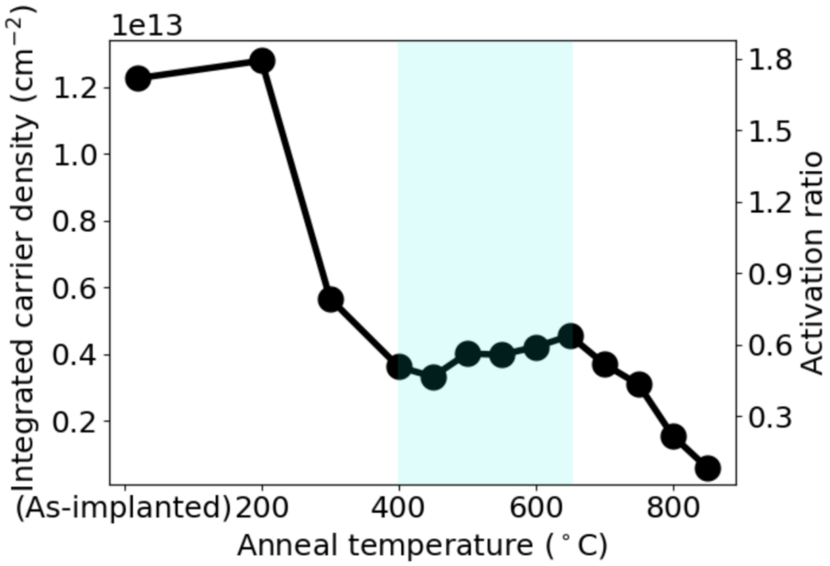


iii) T > 650 °C



- Dark field optical images brighten with roughness
- Loss of dopants results in decrease of electrical activation

Steady electrical activation suggests reduction in implant damage and dopant loss



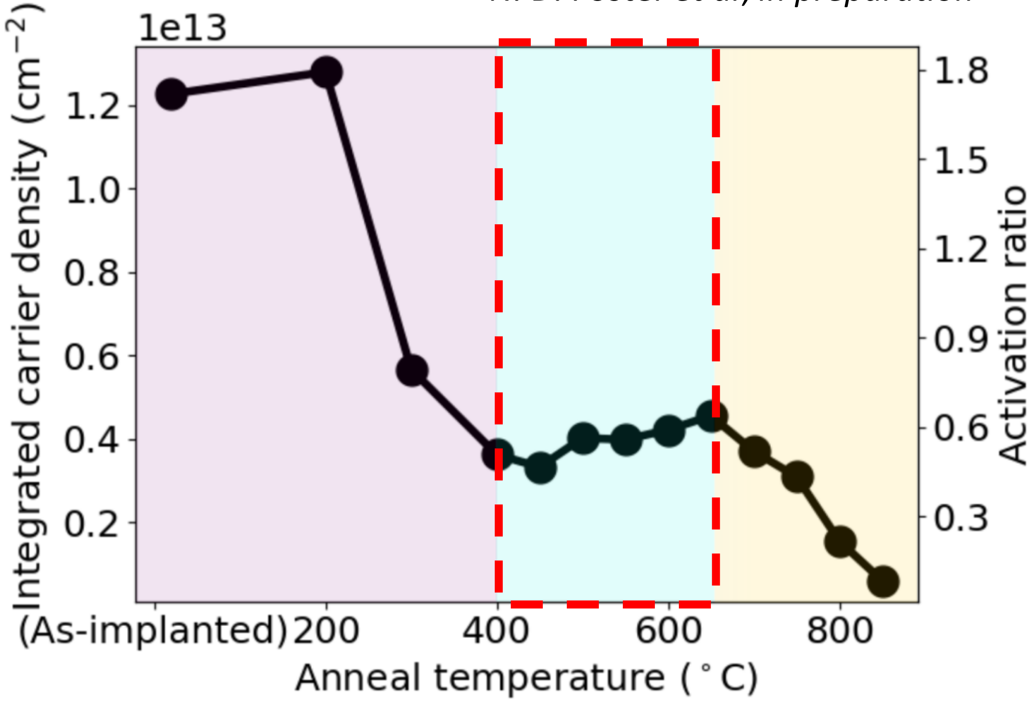
ii) 400 < T < 650 ^{o}C

- High degree of electrical activation (64%) corresponds to integrated carrier density 4.7×10^{12} cm^{-2}
- Implant damage is healed through annealing ✓
- Dopant loss is avoided ✓

Summary & acknowledgments

- Rapid thermal annealing at temperatures 400 < T < 650 ºC heals implant damage **and** avoids dopant loss
- Guides activation parameters for all-electric control of hole-spin qubits in Ge

N. D. Foster *et al, in preparation*



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