Focused Helium Ion Beam Nanofabrication of Superconducting Thin Films

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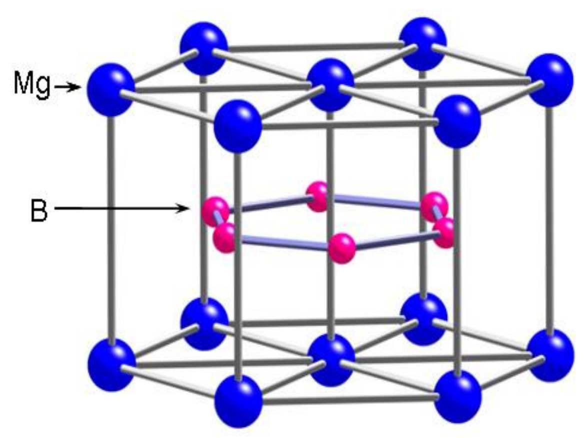
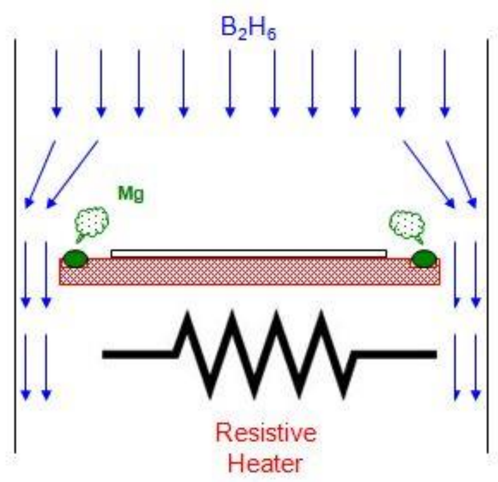
Introduction

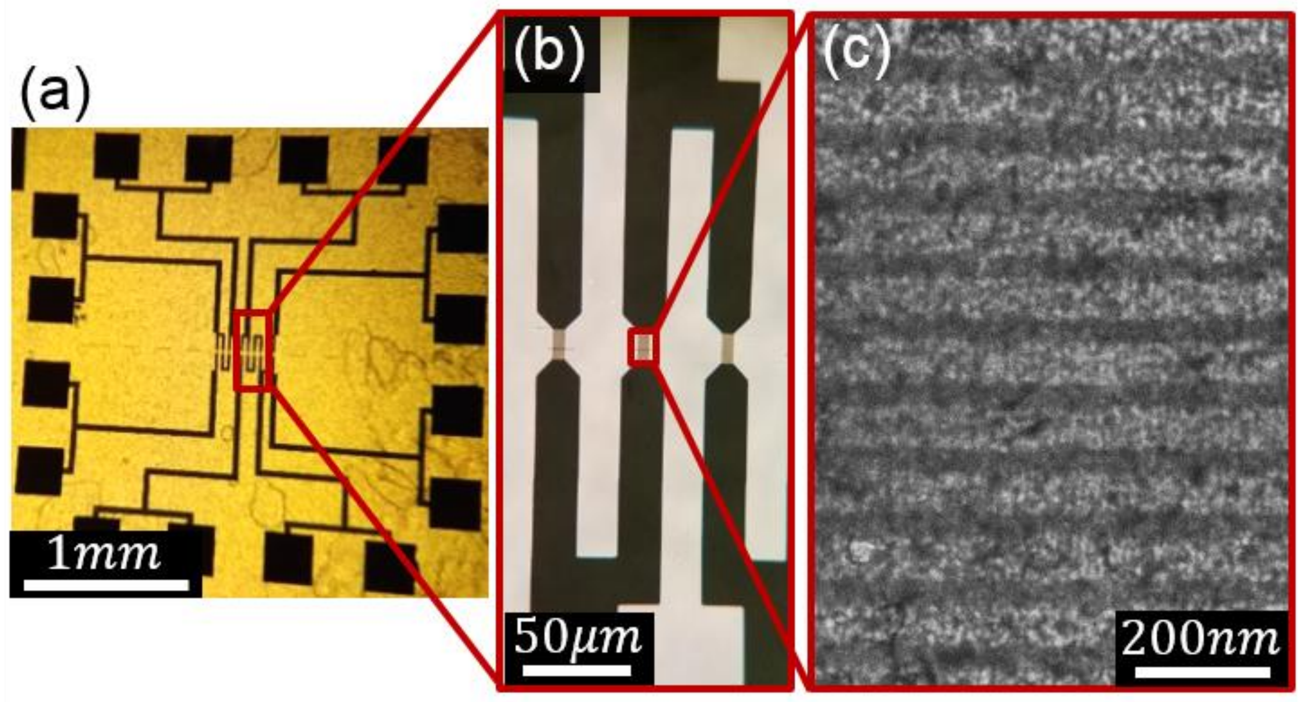
- A reliable and reproducible technique to make Josephson junctions is necessary to scale up superconducting circuits.
- He^+ beam has nominal beam diameter < 0.5 nm making a narrow damaged region in material.
- We fabricated high quality Planar MgB_2 Josephson junctions using focused helium ion beam[2].
- How much is on-chip parameter spreads? Can we lower it?
- Can we develop the lumped arrays instead of distributed arrays?

Film growth and fabrication method





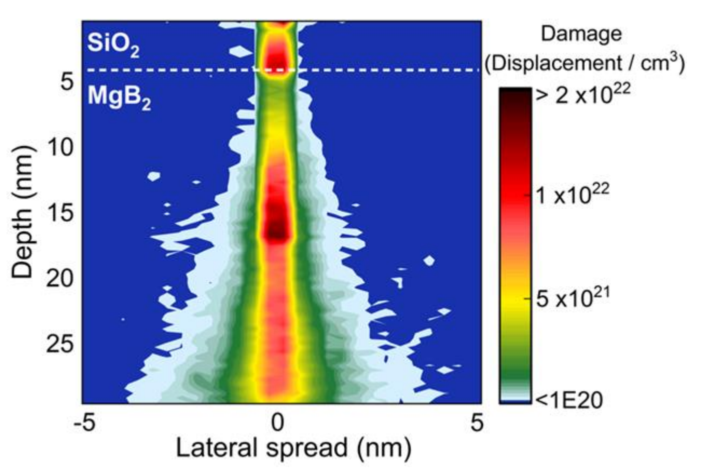
- T_c = 39 K (bulk)/Device operating T > 20 K
- Anisotropic coherence length $\xi_{a\text{-}b}$ = 4-6 nm, ξ_c < 1 nm
- Hybrid Physical-Chemical Vapor Deposition (HPCVD) produces high quality MgB_2 film.

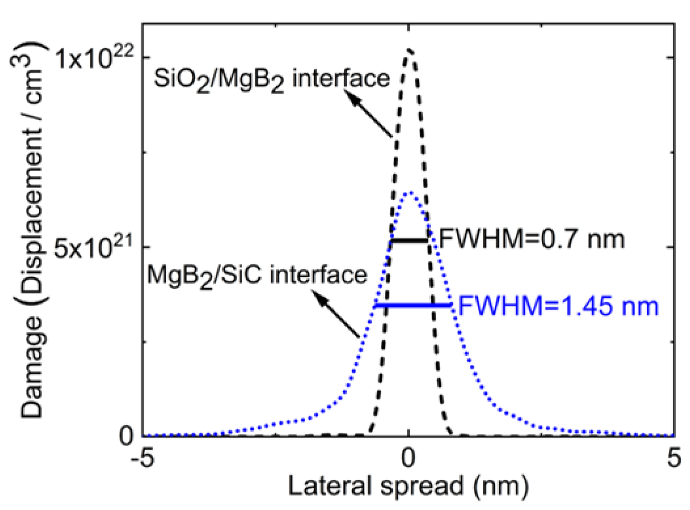


Optical image of the array pattern with meandering micro-strip in the center.

10 single tracks of He^+ at 100nm inter- line spacing.

Ion displacement simulation

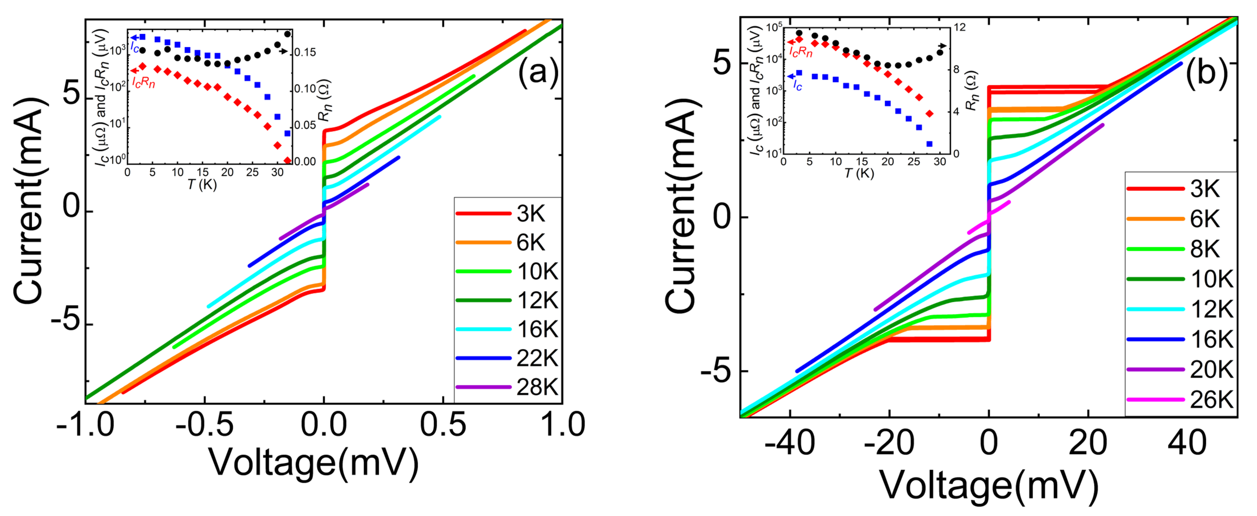




- TRIM simulation of damage density when irradiated with 2.7×10^{16} /cm² He ions.
- The lateral spread of the damage (FWHM) is less than MgB_2 coherence length.

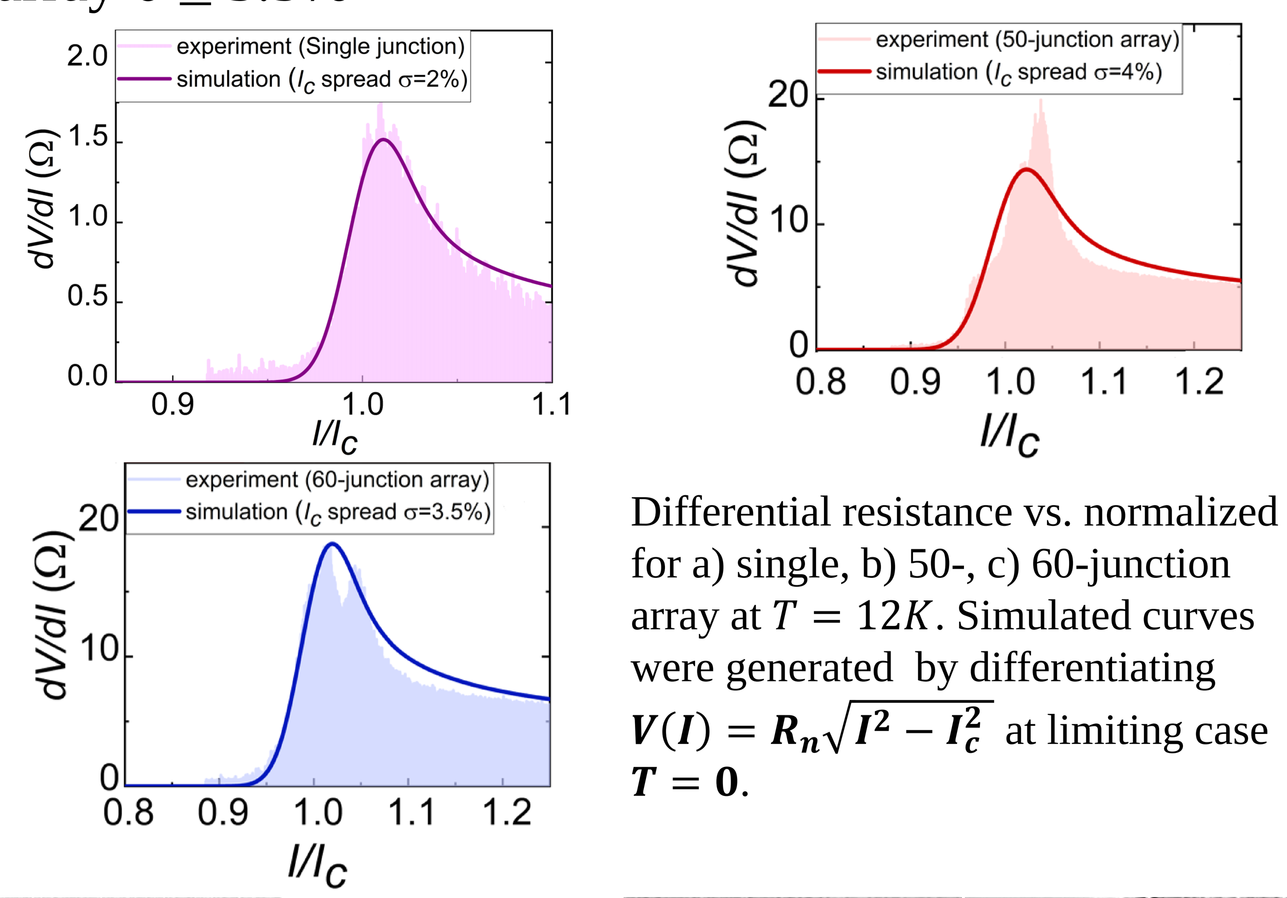
Result

- Critical current independent from N (N number of junctions in array)
- Almost linear increase of R_n with N
- 1 junction $\langle R_n \rangle \sim 0.15\ \Omega$ 60-junction array $\langle R_n \rangle \sim 9.6\ \Omega$

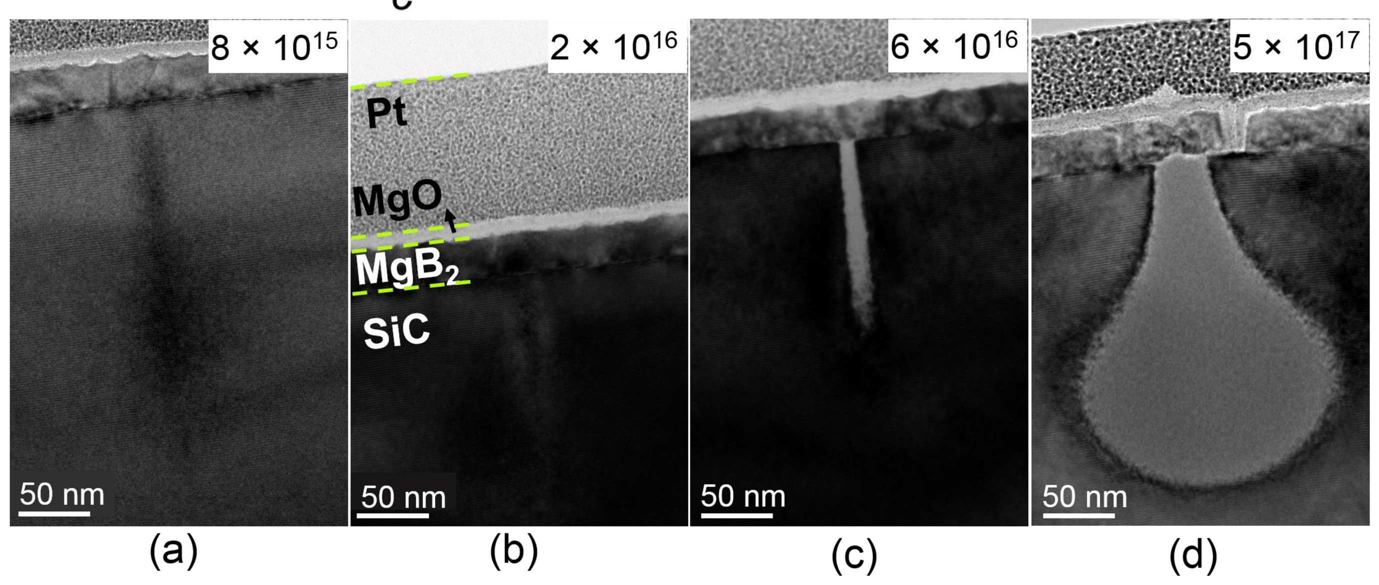


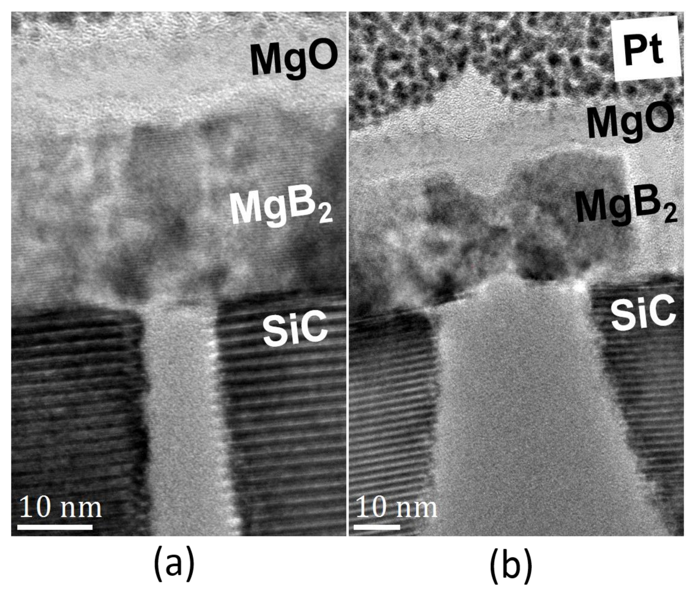
I-V curves at different T for (a) single junction, (b) 60-junction array. Insets show T dependence of R_n (■), I_c (●), I_cR_n (♦).

- Spread of Critical Current
- 1 junction $\sigma \leq 2\%$; 50-junction array $\sigma \leq 4\%$; 60-junction array $\sigma \leq 3.5\%$



Differential resistance vs. normalized I for a) single, b) 50-, c) 60-junction array at $T = 12K$. Simulated curves were generated by differentiating $V(I) = R_n\sqrt{I^2 - I_c^2}$ at limiting case $T = 0$.

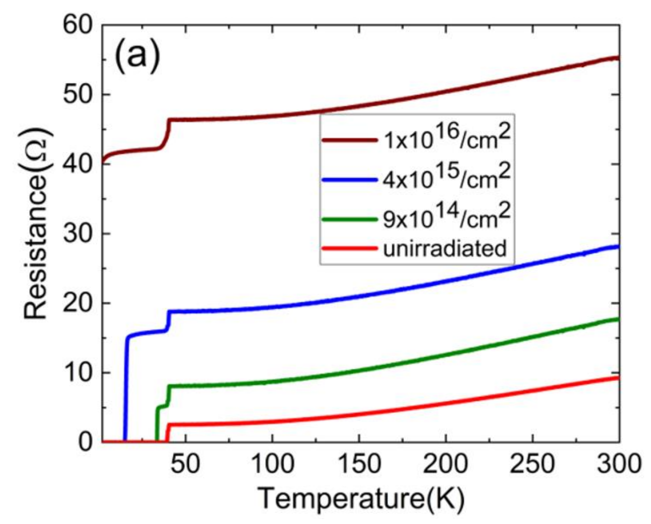


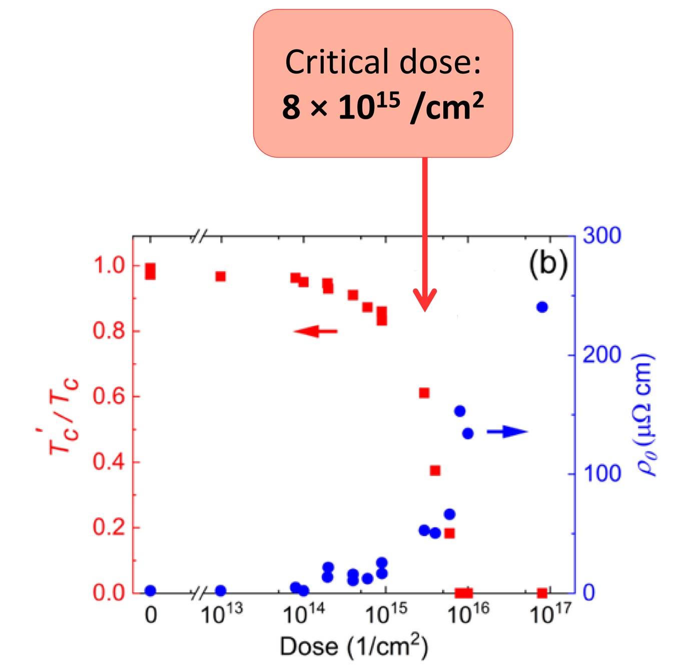


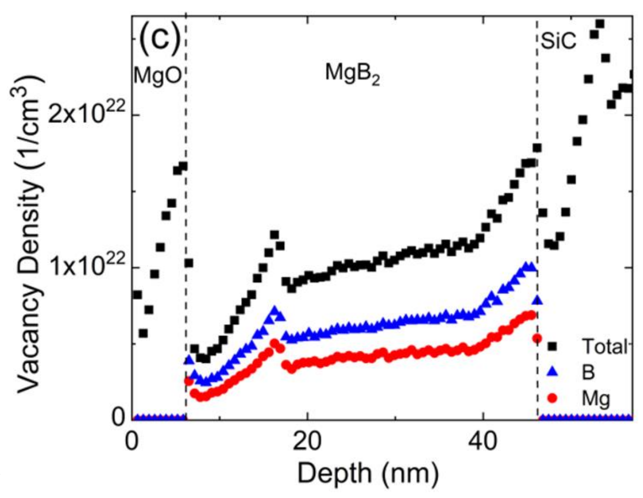
Cross-sectional TEM bright field (BF) images of irradiated regions of four beam spots with four doses and high resolution images for doses of (e) 6×10^{16}/cm², (f) 5×10^{17}/cm².

- Consistent with the TRIM simulation

Discussion







(a) Resistance vs. temperature.
(b) Normalized critical temperature T_c'/T_c and residual resistivity ρ_0.
(c) Vacancy concentration for $MgO/MgB_2/SiC$ configuration at dose 8×10^{15} /cm². (L.Kasaei et al.)

- The total vacancy concentration from TRIM of the order 10^{22} /cm³ leads to complete T_c suppression.

Conclusion

- Direct-writing of 50- and 60- junction series arrays of planar MgB_2 Josephson junctions by focused helium ion beam with excellent uniformity and reproducibility. (Spread of Ic $\sigma \leq 3.5$ %)
- Focused helium ion beam irradiation is applicable to any material that is sensitive to disorder to demonstrate features of the critical dimensions for an array of future devices.

References

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