

Highly tunable NbTiN Josephson junctions fabricated with focused helium ion beam

Aki Ruhtinas^{✉*} and Ilari J. Maasilta^{✉†}

Nanoscience Center, Department of Physics, *University of Jyväskylä*, P. O. Box 35, FI-40014 Jyväskylä, Finland



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We demonstrate a direct writing method for the fabrication of planar Josephson junctions from high-quality superconducting niobium titanium nitride (NbTiN) thin films, by creating local disorder using focused He ion beam irradiation. We control the suppression of superconductivity in NbTiN as a function of the helium ion beam fluence, enabling us to successfully fabricate Josephson junctions with highly tunable weak links ranging from the metallic to the insulating phase, utilizing the continuous nature of the disorder-induced superconductor-insulator transition. We demonstrate the successful fabrication of both superconductor-normal metal-superconductor (SNS) and superconductor-insulator-superconductor (SIS) type of devices, and show that we can achieve an exceptionally wide range (~ 5 orders of magnitude) of critical current densities and junction resistances. The SNS-type junctions follow closely the ideal resistively and capacitively shunted junction behavior, have high characteristic voltages up to ~ 1.5 mV, and show Shapiro steps up to very high orders, while the SIS junctions also follow established theories well. The results suggest that the junctions are suitable for a wide range of applications in superconducting electronics because of the excellent mechanical, electrical, and microwave properties of NbTiN. In particular, as NbTiN has previously been used to fabricate high-quality factor microwave resonators, we see the method as a promising and simple way to realize high-frequency superconducting qubits and other quantum devices using only a single superconducting film.

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I. INTRODUCTION

While weak disorder does not have an effect on the superconducting state [1], strong enough disorder can cause a superconductor to undergo a superconductor-to-insulator transition (SIT) [2]. If such a superconducting film is locally pushed into the strong disorder limit by ion irradiation, the arising SIT quantum phase transition can be exploited in the fabrication of Josephson junctions from a single material, as changing the level of disorder can change the film properties drastically. However, to make a good junction, the disordered region needs to be defined with nanometer resolution. Ion irradiation or ion implantation of weak links is not a modern idea [3], but recent developments in focused ion beam technology have opened up possibilities, such as direct writing of devices in the nanometer scale [4,5]. A high enough spatial resolution became only available in 2007 with the commercial introduction of helium ion microscope (HIM) [6], as it can provide <0.5 nm beam spot size.

In the helium ion direct-write fabrication of Josephson junctions, this high-resolution helium ion beam is used to locally irradiate a superconducting film to introduce disorder and therefore control the suppression of superconductivity, enabling fabrication of highly tunable weak links where both the

width and the strength of the link can be tuned continuously [7]. He ions are needed, instead of heavier ions such as Ga, to significantly reduce the probability of sputtering, which would lead to milling instead of introduction of disorder.

He ion direct writing of Josephson junctions was first demonstrated in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\sigma}$ (YBCO) films [7]. After that seminal study, the method has been applied not only to YBCO thin films to create Josephson junctions and superconducting quantum interference devices (SQUIDs) [8–10] but also to MgB_2 [11] and to $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ [12] thin films. However, these materials are often difficult to work with, and electrical, mechanical, and chemical properties are not ideal for all applications. In contrast, for many superconducting devices, more standard low-temperature superconductors with more ideal Bardeen-Cooper-Schrieffer (BCS)-type behavior are desirable, instead of the complex high-temperature superconducting materials. Superconducting nitrides are such more ideal materials and also seem a promising choice for direct writing, as it is known that a disorder-driven superconductor-insulator transition exists in NbN [13–15], TiN [16,17], and NbTiN [18,19]. Recently, direct He ion writing of NbN has indeed been investigated [20,21], with initial work on junction fabrication.

Here, we focus on using high-quality (critical temperature T_c up to 15.7 K) pulsed laser deposited (PLD) NbTiN as the superconducting material, to which we directly write Josephson junctions with a nanoscale helium ion beam using a helium ion microscope. NbTiN has excellent electrical and mechanical characteristics and high corrosion resistance, which makes it a good choice for Josephson junction fabrication. Moreover, NbTiN is already a state-of-the-art material in many devices, and it has been used, for example, in the

*Contact author: akperuht@jyu.fi

†Contact author: maasilta@jyu.fi

highest-quality factor microwave resonators [22–26], rapid single flux quantum (RSFQ) devices [27], superconducting nanowire single-photon detectors [28,29], and THz-band heterodyne sensing technologies [30,31].

The measured electrical characteristics of the junctions closely follow established theories. Moreover, we show that we can tune both the junction length and the critical current density of the junctions, over five orders of magnitude for the critical current density, making the junctions exceptionally tunable. This type of junction can then be applied to optimize the performance of a wide range of devices, with junction types ranging from normal metal to insulating. Particularly appealing feature of this method is the opportunity to fabricate complete quantum devices, such as high-frequency qubits and parametric amplifiers using only a single NbTiN thin film, reducing the number of interfaces, materials, and processing steps to be optimized, known to be critical factors for performance degradation in superconducting devices through various loss mechanisms [32].

II. DEVICE FABRICATION

A. Film deposition and lithography

Thin films of NbTiN were deposited using the same reactive infrared PLD technique as demonstrated for TiN [33], TaN [34], and NbN [35] before. As a target, we used two different compositions, Nb_{0.39}Ti_{0.61} and Nb_{0.5}Ti_{0.5}, with most of the samples made from the 50/50 target. The composition choice did not have a significant effect on the film properties, with only a small effect on the resulting NbTiN film resistivity. We deposited the films in ultrahigh-purity nitrogen atmosphere using 700 °C substrate temperature and cubic (100)-oriented MgO substrates. MgO substrates were chosen for several reasons. First of all, MgO has a good lattice match to NbTiN, allowing epitaxial growth [36]. Second, the SF₆-based plasma etching step to define the wires stops to MgO. Third and most importantly, MgO can withstand large helium ion fluences without issues with the formation of helium bubbles in the substrate, unlike what can happen in Si, for example [37]. However, we want to stress here that MgO is not the only possible substrate material.

The superconducting properties of our PLD deposited films are excellent, and with 100 nm thick films the superconducting critical temperature T_c is as high as 15.7 K and resistivity is as low as $\sim 35 \mu\Omega \text{ cm}$, on par with the highest-quality results in the literature [38], with the superconducting transition width typically quite narrow ($\sim 50 \text{ mK}$). The critical temperature decreases when the film thickness decreases, and for a 50 nm thickness $T_c \sim 15 \text{ K}$ while for a 22 nm thick film, we have achieved a T_c of 11.5 K. In this study, we have mostly used a film thickness of 35 nm, with a $T_c \sim 13 \text{ K}$.

The bonding pads and superconducting wires were defined to the film using electron beam lithography and subsequent reactive ion etching in SF₆ + O₂ plasma. More details of the device fabrication process are given in the Supplemental Material [36].

B. Helium ion irradiation

Josephson junctions were defined into the superconducting wires using a helium ion beam “direct writing” technique. For

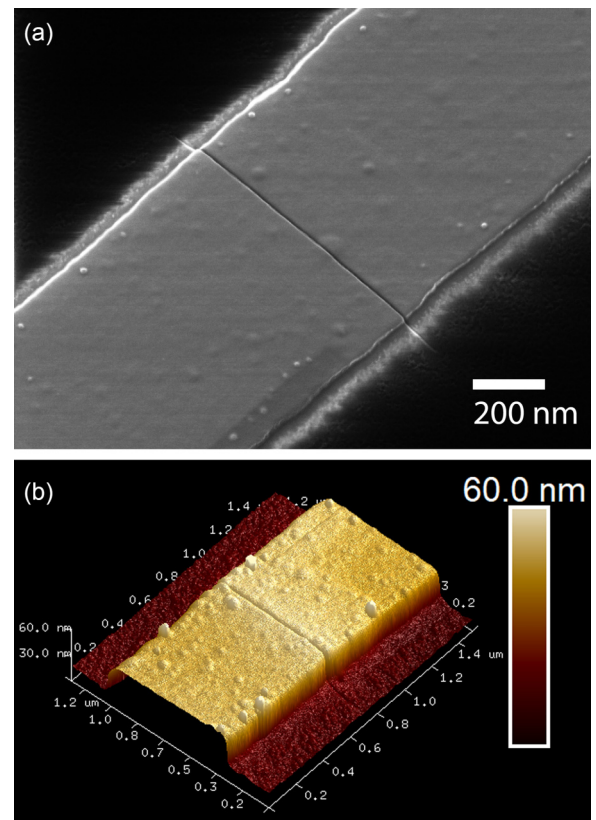


FIG. 1. (a) An HIM and (b) an AFM image of a NbTiN Josephson junction created by helium ion irradiation. The fluence used here was $\sim 6 \times 10^{18} \text{ ions/cm}^2$. The width of the irradiated region in this case is quite wide, $\sim 14 \text{ nm}$, and the superconducting wire is partially milled, as can be seen from both the AFM and HIM images.

this, we used a 30 kV He⁺ beam in a Zeiss Orion Nanofab helium ion microscope with a nominal spatial resolution of 0.5 nm. The junction was defined as a narrow line irradiation, perpendicular to the length of the superconducting wire, creating a weak link between the two electrodes via disorder (Fig. 1). Depending on the spot size and focusing, the width of the irradiated line w_{irr} was varied between ~ 3 and 500 nm. Larger irradiation widths were achieved by using a large spot size and by defocusing the beam significantly. Compared to the He ion beam written YBCO junctions [7], the NbTiN junctions in this study need roughly 2 orders of magnitude more fluence to suppress superconductivity. Thus, in this work a fluence in the range $10^{16} - 10^{20} \text{ He}^+/\text{cm}^2$ was used. After the irradiation, every junction was imaged with a quick HIM scan to ensure that the junction was successfully defined, and to check the resulting linewidth (junction length in the parlance of planar Josephson junctions).

To quantify the possible partial milling of the NbTiN film, we also performed milling experiments with the helium ion microscope with a subsequent atomic force microscope (AFM) measurement. Using that data, we have determined an estimate for the milling depth d_{mill} as a function of the fluence Φ , giving an empirical expression

$$d_{\text{mill}} (\text{nm}) \approx 4.06 \times (\Phi [10^{18} \text{ ion/cm}^2])^{0.68}. \quad (1)$$

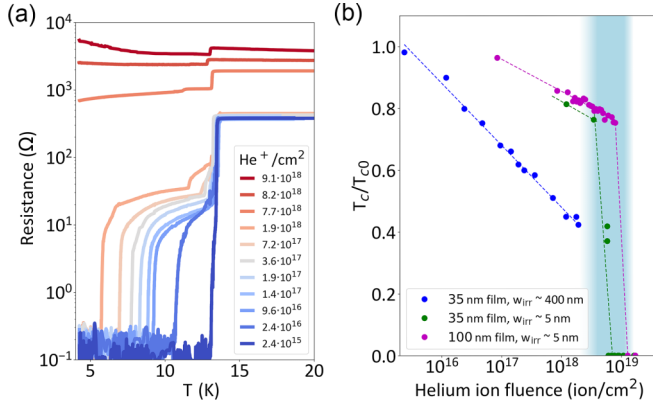


FIG. 2. Suppression of T_c and the demonstration of an apparent disorder driven SIT in NbTiN thin films. Panel (a) shows the resistances of superconducting NbTiN wires after the irradiation of a region of a wire with a helium ion beam using different He ion beam fluences. Wires undergo a transition from superconducting to insulating phase as the helium ion fluence increases, with a suppression of T_c along the way. Width of the irradiated region is $w_{\text{irr}} \sim 400$ nm, except for the three highest fluence samples, for which $w_{\text{irr}} \sim 5$ nm. All samples are from the same chip, with a film thickness 35 nm. Panel (b) shows the suppression of T_c 's of the irradiated regions of a collection of wires from three chips in a semilogarithmic plot, showing a linear dependence of T_c as a function of the logarithm of the ion beam fluence. SIT region is shaded in blue. T_{c0} = critical temperature of the unirradiated film. Samples were measured with a 100 nA excitation at 18.5 Hz.

We use Eq. (1) for thickness corrections to determine more accurate values for the critical current densities J_c and resistivities ρ of the junctions. Derivation of Eq. (1) is presented in the Supplemental Material [36].

In addition to irradiation and milling experiments, we have also simulated the ion irradiation with a simulation code for ion-matter interaction (SRIM) [39]. Using SRIM, we simulated a 30 kV He⁺ beam impinging on a 35 nm NbTiN film on top of a MgO substrate. These simulations [36] show that most helium ions travel through the film, stopping only in the substrate (MgO) after traveling roughly a distance of 150 nm, and that there is only a small lateral straggle when the ions travel through the NbTiN film. The created disorder is concentrated in very narrow lateral region of a few nm, which is good for an accurate junction definition.

III. SUPPRESSION OF SUPERCONDUCTIVITY

In order to investigate the effects of helium ion irradiation on NbTiN thin films first more generally, we have irradiated superconducting NbTiN wires with HIM, using a varying fluence and size (linewidth) of the irradiated region. Results for the resistance vs temperature curves as a function of the irradiation fluence (measured with an excitation current 100 nA at 18.5 Hz) are shown in Fig. 2(a), revealing that helium ion beam irradiation induces strong enough local disorder to suppress superconductivity and ultimately pushes the irradiated region to an insulating phase with increasing fluence. For the large 400 nm linewidth irradiation [blue dots in Fig. 2(b)], the superconducting critical temperature

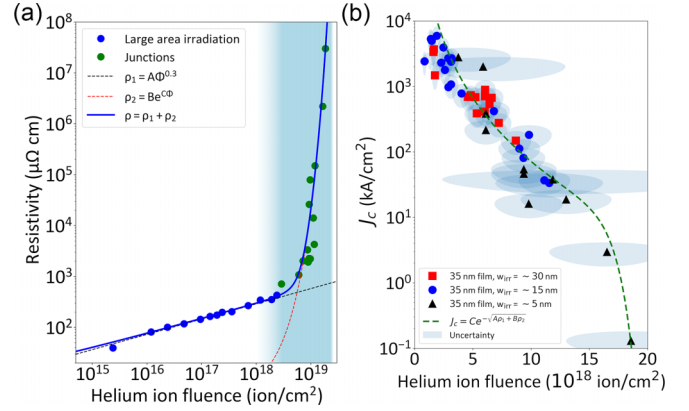


FIG. 3. (a) Resistivities of junctions and large area irradiations (~ 400 nm irradiation) for 35 nm thick films at 4.2 K as a function of the helium ion fluence. Resistivity ρ was determined from the Ohmic region of the IVC. We see that at small fluences resistivity increases as $\rho \propto \Phi^{0.3}$, but around $\sim 5 \times 10^{18}$ ion/cm² it starts to increase exponentially. (b) The dependence of the critical current density J_c for a set of samples measured at 4.2 K as a function of the helium ion fluence. Uncertainties are shown as blue shaded regions; dashed green line is the phenomenological fit described in the main text.

suppression as a function of the helium ion fluence Φ is surprisingly linear in semilogarithmic scale, indicating that $T_c \propto -\log(\Phi)$. This relation allows straightforward and accurate T_c control of the NbTiN film, which may be useful in various applications.

While the irradiations with small widths (~ 5 nm) also have the property $T_c \propto -\log(\Phi)$ at lower fluences [Fig. 2(b)], where the measured apparent T_c now reflects the temperature of the disappearance of the supercurrent due to the presence of the Josephson current, we see in Fig. 2(b) that there is now a sharp transition to a nonsuperconducting, and as we will see in a moment, insulating phase around $\sim 5 \times 10^{18}$ ion/cm² for 35 nm thick films, and this transition shifts to a higher fluence ($\sim 1 \times 10^{19}$ ion/cm²) for 97 nm films. This shift is expected, as there are more atoms to displace when films are thicker. However, there is a lot of energy left in the He ions after traveling through the NbTiN, so that a film thickness increase is not expected to increase the transition fluence linearly. We find that this region [blue region in Fig. 2(b)] is the best for Josephson junction fabrication, as in that case the critical current can be tuned continuously from $\sim I_c$ of the bulk wire down to zero.

To study the transition to the insulating phase further, we also plot the resistivity of the irradiated region for 35 nm thick films at 4.2 K as a function of the fluence in Fig. 3(a). It increases with fluence, first gently as $\rho \propto \Phi^{0.3}$ in the region where the superconducting transition temperature is just lowered, but after a critical fluence value $\sim 5 \times 10^{18}$ ion/cm² exponentially in the region where no superconducting transition was observable. This is evidence that beyond this critical disorder level superconductivity is completely suppressed, with a transition to an insulating state taking place.

The insulating state arising from this apparent superconductor-insulator transition is interesting in its

own right, although not the main focus of this study. We have also seen that the resistivity of the irradiated region increases exponentially over several orders of magnitude from room temperature to cryogenic temperatures. This strong temperature dependence can be fitted well by the Efros and Shklovskii variable range hopping theory [40] (see Supplemental Material [36]), indicating that in the insulating state electrons are localized due to the strong disorder. We should note that the observation of this apparent local SIT does not necessarily imply that we can control the SIT in a macroscopic bulk film under the same type of irradiation conditions.

Finally, we compare our observations to earlier results on HIM irradiation of superconducting NbN films. Our fluence range is not far from the results of Martinez *et al.* [20], who found critical current suppression to zero at 4.2 K at a fluence $\sim 1 \times 10^{18}$ ion/cm² for thinner 5 nm films, but it is smaller than 1×10^{20} ion/cm² that was used by Li *et al.* [21] to fabricate a Josephson junction to a 15 nm NbN film.

IV. JOSEPHSON JUNCTIONS

After the characterization of the apparent SIT as a function of fluence, we proceeded to fabricate several weak links with varying strengths and widths using fluences in the aforementioned transition region, ranging from metallic (SNS) to insulator-type (SIS) junctions. Figure 1 shows an example of microscope images of a fabricated junction, where the junction is formed by a perpendicular irradiation line in the superconducting wire. In the subsections below, we present results on tuning of critical current density, on dc transport measurements, on weak link properties, on critical current as a function of temperature, on characteristic voltages, on microwave measurements, and finally on magnetic field measurements.

A. Tuning of critical current density

To be able to reproducibly fabricate junctions, we have determined experimentally how the critical current density J_c depends on the helium ion fluence within the SIT region in Fig. 2(b). The results of these experiments are shown in Fig. 3(b), where we plot the critical current densities J_c of several junctions fabricated to ~ 500 nm wide and 35 nm thick wires. We see that J_c can be tuned continuously by an exceptionally wide range of five orders of magnitude. We note that in the determination of J_c , we have taken into account the effect of the change of the effective junction area by partial milling, which was determined with AFM [36]. As the fluence was calculated using the full width at half maximum (FWHM) of fits to junction linewidth profiles in HIM images [36], in some cases the error in fluence determination is sizable. From Fig. 3(b), we find that J_c is roughly exponentially decaying function of the helium ion fluence.

To understand this behavior in more detail, we note that the relevant length scale for a normal metal weak link is the normal metal coherence length ξ_N in the irradiated normal

metal region, with ξ_N is given by [3]

$$\xi_N(T) = \sqrt{\frac{\hbar D}{2\pi k_B T}}, \quad (2)$$

where D is the diffusion coefficient. On the other hand, the Einstein relation connects the diffusion coefficient and the resistivity ρ as $D = 1/(e^2 g(E_F) \rho)$, where $g(E_F)$ is the density of states at Fermi energy; from Eq. (2), we see that $\xi_N \propto 1/\sqrt{\rho}$. The critical current density in SNS Josephson junctions follows approximately exponential dependence $J_c \propto e^{-L_j/\xi_N}$ [3], where L_j is the junction length, so that we expect J_c to depend on the resistivity as $J_c \propto e^{-a\sqrt{\rho}}$. Assuming that the fluence Φ influences mostly by modifying ρ , we use the fit of the $\rho(\Phi) = \rho_1 + \rho_2$ data shown in Fig. 3(a) as an input and fit the critical current data in Fig. 3(b) with a function $J_c = c \exp(-\sqrt{a\rho_1 + b\rho_2})$. This rough phenomenological modeling seems to explain the main features of the $J_c(\Phi)$ data from small to large fluences.

Because the SIT region is relatively narrow in Φ , precise control of the helium ion beam is needed for reproducible fabrication of junctions. This is especially true for the narrowest < 10 nm junctions [black triangles in Fig. 3(b)], as small changes in the irradiation width change Φ and thus I_c drastically. From the large area irradiations, we have seen that there is certainly a strong suppression of T_c without substantial ion beam milling of the sample, but with the narrow irradiations the required ion fluences are so high that there is substantial milling, as seen from the AFM data [36]. However, we estimate that in all junctions with $J_c > 10$ kA/cm², there is still over 10 nm of film thickness left. Since in our pristine 10 nm NbTiN films T_c is as high as ~ 7 K, the suppression of T_c and I_c is clearly not caused by milling but by ion beam-induced disorder.

This conclusion is also supported by the most insulating junctions with $J_c < 10$ kA/cm², for which we estimate [36] that there is at least ~ 5 nm of the film left, an amount that would still be superconducting if in a pristine state.

B. dc transport measurements

A set of eight overdamped Josephson junctions (JJ1-JJ8) fabricated with helium ion direct writing were characterized via dc transport measurements either down to 1.5 K with a liquid helium evaporation cryostat or down to 4.2 K with a liquid helium bath. The measured experimental parameters of all the junctions are collected in Table I. We measured the current-voltage characteristics (IVC) at different temperatures using a battery-powered sweep box and a voltage divider, to achieve a low noise level. Voltage and current were measured using Ithaco preamplifiers (models 1201 and 1211), and the differential conductance was determined with numerical differentiation of the IVC. In Figs. 4 and 5, we show dc transport measurements of five representative Josephson junctions of varying strength of the weak links. Figure 4 presents transport measurements of four SNS-type junctions, whereas Fig. 5 shows results for an SIS-type junction. We remark that as the junction is continuously tunable from a superconducting to an insulating state, this division can be somewhat artificial. Here, we have classified the junction types to SNS or

TABLE I. Junction parameters at 1.5 K.

Name	JJ1 ^a	JJ2	JJ3	JJ4	JJ5 ^a	JJ6	JJ7 ^{a,b}	JJ8 ^{a,b}
Lead T_c (K)	12.84	13.90	14.2	15.70	14.2	13.00	14.2	13.80
Film thickness (nm)	35	48	35	100	35	35	35	35
Milled thickness (nm)	26	27	16	77	13	16	7.7	5.4
Junction width (nm)	1500	2030	620	300	720	860	660	1290
Junction area A_j (μm^2)	0.040	0.055	0.010	0.023	0.009	0.014	0.0050	0.0069
Fluence Φ ($10^{18}\text{He}^+/\text{cm}^2$)	2.9	11	9.4	13	~ 12	9.8	17	19
Junction length L_j (nm)	14	30	7	12	3	3	3	4
I_c (μA)	390	44	9.2	9.0	3.6	2.2	0.15	9×10^{-3}
R_n (Ω)	2.5	4.8	180	160	470	173	13.2×10^3	1.7×10^5
$I_c R_n$ (mV)	0.98	0.21	1.6	1.4	1.7	0.38	2.0	1.5
J_c (kA/cm^2)	978	79.6	90.6	39.1	38.5	16.1	2.96	0.13
$R_\square$ ($\text{k}\Omega$)	0.27	0.32	15.5	4.00	110	49.6	2900	5.5×10^4
ρ ($\mu\Omega\text{cm}$)	710	880	2.6×10^4	3.1×10^4	1.5×10^5	7.9×10^4	2.2×10^6	3.0×10^7

^aParameters measured at 4.2 K.^b I_c estimated from quasiparticle current inflection point.

SIS simply based on the general shape of the current-voltage characteristics.

To extract more precisely the critical current (I_c) and normal state resistance (R_n) values, the IVCs of SNS-type junctions were fitted at selected temperatures using the resistively and capacitively shunted junction (RCSJ) model [42] (see Supplemental Material for more details [36]). From these fits, we extracted values for I_c , R_n , and the junction capacitance C . However, because self-heating effects quite closely resemble capacitive effects on the IVCs [3,43], we used the capacitance merely as a fit parameter, as it does not correspond to the estimated geometrical junction capacitance.

We believe that the hysteresis seen in junction JJ1 is most likely of thermal origin instead of capacitive. In addition, because JJ7 and JJ8 have low I_c and were measured only down to 4 K, thermal noise suppresses the supercurrent significantly [41], and thus for JJ7 and JJ8 we estimated it from $I_c \approx I_g \pi/4$, where I_g is the quasiparticle current inflection point [44].

The remaining junction region film thickness after the irradiation, the junction length L_j (the width of the HIM irradiated region), and the fluence reported in Table I were estimated with the help of HIM and AFM images, as described in the Supplemental Material [36]. However, for junction JJ5, the estimation of fluence has higher than usual uncertainty as

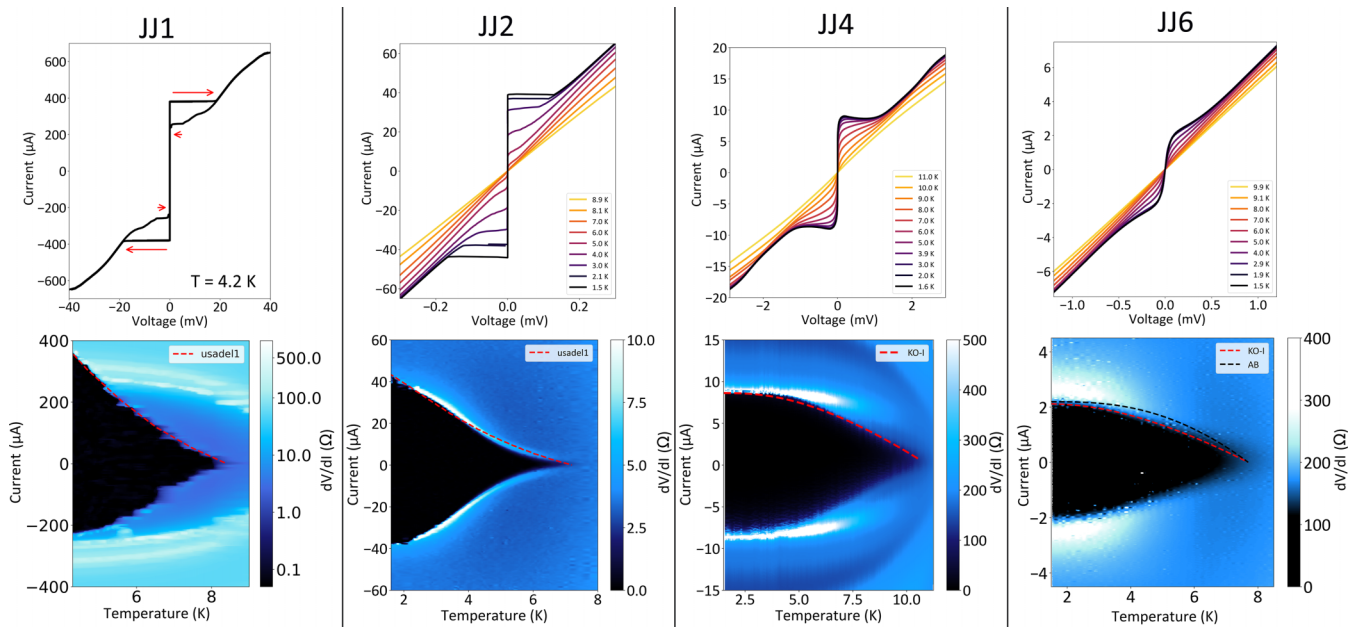


FIG. 4. dc transport measurements of four representative Josephson junction devices: JJ1, JJ2, JJ4, and JJ6, fabricated using different helium ion fluences and different superconducting wire geometries, listed in Table I. Top row: current-voltage characteristics as a function of T ; bottom row: differential resistance as a function of temperature and current. For all junctions, comparison to different theories are shown by the dashed lines. Usadel1: numerical solution of Usadel equations; KO-I: Kulik and Omelyanchuk theory; and AB: Ambegaokar-Baratoff theory, as explained in the text. Noise rounding [41] is visible for JJ6.

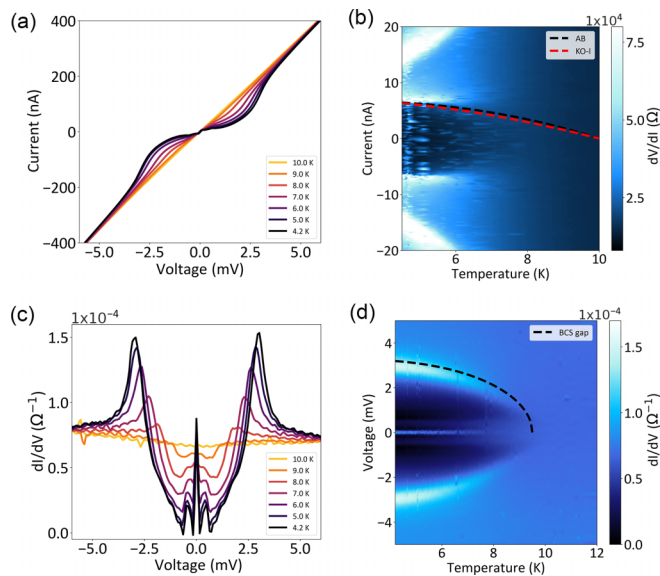


FIG. 5. dc transport measurements of Josephson junction JJ7 fabricated with high enough fluence to push the barrier to the insulating state, as a function of T . The junction is clearly SIS type, as can be seen from the IVC (a) and the dI/dV plots (c), (d). Panel (b) shows dV/dI as a function of T and I , with both KO-I and AB predictions for $I_c(T)$ shown in the plot. Temperature dependence of the superconducting gap in panel (d) follows the BCS theory well with $\Delta \approx 1.5$ meV.

we observed a slight shift in the beam position during the writing.

From the transport measurements, we conclude that it is possible to tune the critical current I_c all the way from the intrinsic value of the superconducting leads continuously down to zero. Here, we demonstrated explicitly that I_c and R_n can be controlled by five orders of magnitude, as for junctions JJ1-JJ8 I_c varies from 390 μ A (JJ1) to 9 nA (JJ8) and R_n from 2.5 Ω (JJ1) to 170 k Ω (JJ8) (Table I). The junction dimensions such as the film thickness, the superconducting wire width w , and the junction length L_j vary between junctions JJ1 and JJ8, showing flexibility of the method. JJ4 was fabricated from a 100 nm thick film, demonstrating that direct writing method is feasible for films thicker than the most commonly used ~ 30 nm thickness in direct HIM writing [7,11]. In addition, we have demonstrated that fabrication of longer junctions is also possible with the direct write method, as JJ2 has $L_j = 30$ nm. For that case, the resistivity of the barrier is relatively low, but the long junction length reduces the critical current.

C. Weak link properties

When milling was taken into account, the calculated junction resistivities ρ for SNS-type devices ranged from $\sim 700 \mu\Omega \text{ cm}$ (JJ2) to $\sim 1.5 \times 10^5 \mu\Omega \text{ cm}$ (JJ5) (Table I). These are high values for metals, and therefore the weak links with the strongest disorder are in the limit of not being good metals anymore. The corresponding sheet resistances $R_\square$ vary between $\sim 0.3 \text{ k}\Omega$ (JJ1, JJ2) and $\sim 110 \text{ k}\Omega$ (JJ5). In all of the SNS-type junctions, the temperature dependence of R_n is very weak, indicating still a metalliclike conductivity.

For junction JJ4, we also confirmed the lack of temperature dependence down to $T \sim 0.1 \text{ K}$ [36]. In NbTiN, a Bose metallic state [45] has been experimentally observed when the sheet resistance $R_\square$ is above the superconducting resistance quantum $R_Q = h/4e^2 = 6.45 \text{ k}\Omega$ [19]. From the measured $R_\square$ values, it seems that junctions JJ3-JJ6 are in the vicinity or above this limit, suggesting a possible presence of the Bose metal phase. Junctions JJ5 and JJ6 have high enough $R_\square$ that based on Ref. [18], these junctions should already be in the insulating side of the SIT, indicating that they could possibly also be overdamped SIS junctions. This division is however somewhat artificial as these weak links are continuously tunable.

For the more clearly SIS-type junctions JJ7 and JJ8, the calculated barrier resistivities ρ (with milling estimation taken into account) were ~ 0.02 and $\sim 3 \Omega \text{ m}$, respectively. Interestingly, these resistivities have values corresponding to the barrier being in between a good metal and a good insulator. For a junction dominated by tunneling, it is the specific resistance $R_n A_j$ that characterizes the barrier strength, in contrast to a locally defined resistivity. We obtain values 66 $\Omega \text{ m}^2$ and 1.17 $\text{k}\Omega \mu \text{m}^2$ for junctions JJ7 and JJ8, respectively, which are in the range of typical AlOx tunnel barriers [46,47]. However, as the AlOx thickness is typically only around 1–2 nm, the devices in this study have lower barrier heights than AlOx-based SIS devices. To quantify this, we estimated the barrier heights ϕ_0 and lengths by fitting the simplest quadratic Simmons model [48,49] $G(V) = G_0(1 + V^2/V_0^2)$ to conductance-voltage data up to a higher voltage range ($\sim 50 \text{ mV}$) at a temperature of 20 K. From the fits, we obtain the effective barrier heights for junctions JJ7 and JJ8, which are close to each other, $\phi_0 \sim 35 \text{ meV}$, but almost two orders of magnitude lower than the typical values ($\sim 1.5 \text{ eV}$) for SIS junctions with aluminum oxide barriers [49,50]. From the fits, we can also obtain the barrier length (thickness), giving 2.6 and 3.8 nm for junctions JJ7 and JJ8, respectively, corresponding well to the values for L_j determined from the HIM images (Table I). We have also extracted similar results from other SIS junctions fabricated the same way, so we can say that within the parameter range explored so far, this fabrication method creates SIS junctions with low ($\phi_0 < 100 \text{ meV}$) and wide ($L_j \sim 3 \text{ nm}$) barriers.

To gain more insight into the SIS junction properties in addition to the normal state tunneling resistance R_n , we also determined the zero temperature superconducting gap $\Delta = \Delta(0)$ and the Dynes broadening parameter Γ [51] from the fits to the quasiparticle tunneling model [42,52] (see the Supplemental Material for more details [36]). The obtained superconducting gaps were $\Delta = 1.5 \text{ meV}$ (JJ7) and 1.1 meV (JJ8), substantially lower than the gap in the leads ($\sim 2.4 \text{ meV}$). However, this is expected, as the ion beam can suppress the T_c to some extent also in the proximity of the irradiated line due to the Gaussian beam shape. The Dynes broadening parameters for junctions JJ7 and JJ8 were $\Gamma = 0.18\Delta$ and 0.25Δ .

Junction JJ7 has a high barrier transparency within the context of SIS junctions. This is reflected in its IVC as additional subgap conductance peak features [Fig. 5(c)], most likely due to multiple Andreev reflections (MAR), which have been predicted and observed for transparent enough SIS junctions

[53–55]. Indeed, the value of J_c of junction JJ7 falls in the range of 1–10 kA/cm², where MAR features were observed in Ref. [53] for Nb junctions. We have also measured another similar SIS junction down to ~ 100 mK to confirm that the insulating state persists down to such low temperatures without a hidden, low-temperature transition to the superconducting state.

D. Critical current as a function of temperature

From the measured $\frac{dV}{dT}(T, I)$ maps [Fig. 4, bottom panels, and Fig. 5(b)], we can extract the temperature-dependent critical current $I_c(T)$ that can be used to clarify further the weak link properties. We observe that at the lower temperature end of the data, the temperature dependence $I_c(T)$ gets much weaker as the barrier strength increases (JJ1 $\rightarrow$ JJ7; see the Supplemental Material [36] for the data on JJ3 and JJ5). This is expected from theory, as $I_c(T)$ scales exponentially with disorder in the case of diffusive metallic barriers, and the saturation at low temperatures is signature of either an insulating barrier or a very strong diffusive barrier [3]. We do not need to consider the clean limit $l > L_j$ here, as the barrier is highly disordered due to the irradiation. An estimate for the mean free path l in the barrier region can be obtained from literature [56], where for NbTiN of similar resistivity ($\sim 500 \mu\Omega$ cm) as the weakest barrier devices in this study (JJ1 and JJ2), a value $l = 2.4 \text{ \AA}$ was measured, putting even the shortest junctions in this study ($L_j = 3 \text{ nm}$) clearly in the diffusive limit $l < L_j$.

To get a more quantitative analysis of $I_c(T)$, we performed numerical modeling, assuming diffusive transport in the weak link. For $I_c(T)$ in junctions JJ1 and JJ2, a numerical simulation was performed using *usadel1* code [57] that solves the quasiclassical Usadel equations in the diffusive limit. Simulation fits using this code are shown as dashed lines in Fig. 4 for junctions JJ1 and JJ2, showing good agreement. As a fit parameter, we used Δ/E_{th} , where the Thouless energy E_{th} represents the characteristic energy scale of the SNS junction, defined as $E_{\text{th}} = \hbar D/L_j^2$, where D is the diffusion coefficient and L_j is the junction length.

For junction JJ1, we found a good fit to $I_c(T)$ with $\Delta/E_{\text{th}} = 6$, so that $E_{\text{th}} \approx 240 \mu\text{eV}$, from which we determine the diffusion constant to be $D \approx 0.7 \text{ cm}^2/\text{s}$ using the bulk value of the gap. Thus, from Eq. (2) the normal coherence length $\xi_N \sim 4.5 \text{ nm}$ at 4.2 K. This puts junction JJ1 well into the long junction limit $L_j > \xi_N$. However, an excess current scaling factor $a = 1.8$ was needed to fit the data. In the IVC of JJ1 (Fig. 4), we also see additional apparent critical currents, most likely due to the ion beam irradiation induced suppression of superconductivity in the vicinity of the junction.

The best fit to $I_c(T)$ curve for JJ2 was achieved for $\Delta/E_{\text{th}} = 5$, so that $E_{\text{th}} \approx 250 \mu\text{eV}$ and $D \approx 3.4 \text{ cm}^2/\text{s}$. The Thouless energy E_{th} is similar to JJ1, but as junction JJ2 is longer, the obtained diffusion constant is larger. Also, the fit was not as good as with JJ1: For JJ2, it was possible to reproduce accurately either the behavior at low temperatures or at high temperatures separately, but for the overall best fit a compromise was needed, as shown in Fig. 4. This could be because by using Eq. (2) and D determined from the fit, we get $\xi_N(4.2 \text{ K}) \approx 10 \text{ nm}$ and $\xi_N(1.5 \text{ K}) \approx 17 \text{ nm}$, showing that the coherence length begins to approach the junction

length (30 nm) at the low-temperature end, causing likely a crossover from the long junction limit to the short junction limit as T is lowered. The scaling factor for I_c in the fit was $a = 0.21$. Interestingly, also for all other junctions fabricated with $w_{\text{irr}} \approx 30 \text{ nm}$ and $I_c \sim 10\text{--}50 \mu\text{A}$, we always have a similar $I_c(T)$ behavior to JJ2. Therefore, we conclude that the $I_c(T)$ properties for JJ2 are common for these type of junctions, although not perfectly described with the theory presented here.

We used the *usadel1* code also for junctions JJ3–JJ8, but found that the Kulik and Omelyanchuk theory (KO-I) [58] for short 1D diffusive weak links ($\ell \ll L_j \ll \xi_N$) fits the data well for these junctions, and the full Usadel theory is not needed. In KO-I theory, the supercurrent is given by

$$I(T, \varphi) = \frac{2\pi k_B T}{e R_n} \sum_{\omega_n} \frac{2\Delta(T) \cos(\varphi/2)}{\Omega_n} \times \arctan \left[\frac{\Delta(T) \sin(\varphi/2)}{\Omega_n} \right], \quad (3)$$

where $\Omega_n^2 = (\hbar\omega_n)^2 + |\Delta(T)|^2 \cos^2(\varphi/2)$, φ is the phase difference, and Matsubara frequencies ω_n are defined such that $\hbar\omega_n = \pi k_B T (2n + 1)$. This same expression was also derived from the generalization of point contacts, valid for arbitrary level of disorder, when a large number of channels and diffusive limit $\ell \ll \xi_N$ are assumed [59]. Even more importantly, the KO-I equation turns out to be valid for tunnel junctions with a uniform spatial distribution of localized states [59,60]. As mentioned above, the insulating phase induced by disorder has presumably localized states, and it is therefore possible that $I_c(T)$ follows KO-I theory even on the insulating side of the transition.

To determine $I_c(T)$ using the KO-I theory, we solved the maximum supercurrent from Eq. (3) numerically by summing the Matsubara frequencies up to $n = 10^5$. The superconducting gap $\Delta(T)$ was calculated with the BCS temperature dependence [42] and using $\Delta(0) = 2k_B T_c$ that has been shown to be more suitable for nitrides [61]. Results of these calculations are shown in Fig. 4 (bottom panel) as dashed lines with the label KO-I, where the only fitting parameters used are an overall scaling factor a and T_c .

For junctions JJ1 and JJ2, it is clear from the above that the approximation for a short junction $L_j \ll \xi_N$ is not fulfilled and KO-I theory cannot be used. However, when the J_c of a junction decreases, we start to have increasingly better fits to the KO-I theory. For JJ3, we can get an approximate fit to the KO-I theory with a prefactor $a = 0.45$, but there is some deviation between $I_c(T)$ and the KO-I result left [36]. When *usadel1* code was used for JJ3, we saw that the KO-I limit of the code $\Delta/E_{\text{th}} \ll 1$ is needed for the best fit, indicating that the full Usadel theory does not explain the deviations any better than the KO-I theory.

For junctions JJ4–JJ6, the fits to the KO-I theory are very good, indicating that these junctions are in the limits where the KO-I theory is applicable. For JJ4, the best fit is achieved with a prefactor $a = 0.35$ (Fig. 4) showing only a small deviation between the KO-I theory and the measured $I_c(T)$. We have also measured junction JJ4 down to $\sim 120 \text{ mK}$, but as expected the IVC did not change [36]. For JJ5, we get a good fit with a prefactor $a = 0.7$, and the deviation between measured the

$I_c(T)$ and the KO-I theory begins to be negligible [36]. The apparent negative differential resistance region visible in the IVCs of junctions JJ4 and JJ5 is most likely due to a self-heating effect [3].

For JJ6, we also compare the data to the Ambegaokar-Baratoff (AB) theory [62]

$$I_c(T) = \frac{\pi \Delta(T)}{2eR_n} \tanh\left(\frac{\Delta(T)}{2k_B T}\right), \quad (4)$$

valid for SIS tunnel junctions without localized states in the barrier. We observe that the AB fit for JJ6 (black dashed line in Fig. 4) is not as good as the KO-I theory fit (red dashed line). As the KO-I theory fits almost perfectly to the measured $I_c(T)$ s of junctions JJ5 and JJ6, these junctions must have either a diffusive normal metal barrier or an insulating barrier with localized states. For JJ6, the purely theoretical $I_c R_n$ value was significantly higher than the measured one, where in fits we had to use prefactors $a = 0.14$ for the KO-I theory and $a = 0.18$ for the AB theory to get good fits.

For junction JJ7, it is more challenging to fit theoretical predictions to the measured $I_c(T)$, as for low I_c junctions I_c is further suppressed by thermal noise [63,64]. We can estimate the thermal noise parameter [41,64] $\Gamma_n = 2\pi k_B T / (I_c \phi_0)$, where I_c is the theoretical critical current given by Eq. (4) and ϕ_0 is the superconducting flux quantum, and get $\Gamma_n \approx 1$, indeed predicting a significant suppression of the measured I_c . We have nevertheless fitted both AB and KO-I predictions to the measured $I_c(T)$, and both seem to fit data fairly well [Fig. 5(b)], with $a = 0.033$ and $a = 0.027$, respectively, so no clear conclusions about the nature of the barrier can be drawn at this stage.

E. Characteristic voltages

The characteristic voltage $I_c R_n$ values were also determined for each junction (Table I). All SNS-type junctions (JJ1-JJ6) feature relatively high $I_c R_n$ values, ranging between 0.2 and 1.7 mV. From the RCSJ fits, it can be seen that an excess current contribution in these junctions is mostly small, and for example, for junction JJ2, the excess current contribution is essentially zero. This can be seen both from the RCSJ fit [36] and below in Sec. IV G, where the critical current is completely suppressed at the nodes of the Fraunhofer pattern. SNS junctions with the highest $I_c R_n$ are JJ3-JJ5, which have characteristic voltages of ~ 1.5 mV. One possible explanation for the high values is that the sheet resistance of these junctions is quite close to R_Q , and there is evidence that $I_c R_n$ values for weak links closer to the phase transition are higher [27]. Because of a small nonlinearity in the IVC, it is difficult to estimate the excess current precisely, but based on the RCSJ fits, its contribution is below 10% for JJ4. Hence, the high $I_c R_n$ is not caused by an excess current contribution. For junctions JJ3 and JJ5, there are signatures of MAR [65] in the IV characteristics [36], and therefore there is some excess current carried by MAR. For JJ5, we estimate the excess current to be $\sim 0.6 \mu A$, yielding a corrected $I_c R_n \approx 1.4$ mV (noncorrected value ≈ 1.7 mV). For junction JJ3, the excess current contribution is smaller, below 10%. The achieved $I_c R_n$ values are already suitable, for example, for high-frequency RSFQ applications.

F. Microwave measurements

In order to characterize the junctions further, we performed electrical measurements of JJ2 under microwave (RF) irradiation at 4.2 K. We used two RF frequencies, 6 and 11 GHz RF produced with an Anritsu 68367C signal generator. The minimum signal output used was -10 dBm, but to get a lower power output for the measurement we used a 20 dBm attenuator in the RF line. The RF signal was carried into the cryostat via a low loss coaxial cable, and the RF radiation was coupled to the sample with a simple loop antenna. All microwave measurements were carried out by scanning the RF output power with a fixed frequency, and measuring simultaneously the dc current-voltage I - V characteristics and the differential resistance vs voltage (dV/dI - V), using a four-wire lock-in technique at each power level.

For a theoretical comparison, we performed RCSJ simulations for the IV curves, and found that at 4.2 K, the junction behavior follows well the simpler RSJ model [42] limit, where the value of capacitance is negligibly small. This model was then used to simulate the RF modulated response of the junction vs dc current and RF power (Shapiro map) [36].

Figures 6(a) and 6(d) first show examples of IVCs of junction JJ2 under 6 and 11 GHz RF illumination, respectively, demonstrating clear Shapiro steps and a good agreement with the RSJ model simulations. The corresponding measured full Shapiro maps are shown in Figs. 6(b) and 6(e). Comparison to the RSJ model simulations of the Shapiro maps [Figs. 6(c) and 6(f)] demonstrates nearly ideal behavior. There is very little deviation between the experiment and the simulation, indicating a high-quality junction. The Shapiro steps are visible up to high order of >20 for the 6 GHz illumination.

G. Magnetic field measurements

Magnetotransport measurements were performed at 4.2 K using a liquid helium dipstick and a 4 T superconducting magnet, with a magnetic field B applied perpendicular to the chip, i.e., along the film thickness direction. The measurements were performed by scanning the coil current and measuring dV/dI directly using a four-wire lock-in technique.

Before discussing the experimental results, we comment on the theory. For the more usual case of a rectangular sandwich-type uniform junction, with the lateral dimensions smaller than the Josephson penetration depth λ_J (small junction limit), the critical current is expected to follow the Fraunhofer pattern [42,66]

$$I_c(B) = I_{c0} \left| \frac{\sin(\pi BA/\phi_0)}{\pi BA/\phi_0} \right|, \quad (5)$$

where A is the effective junction area perpendicular to the field and $\phi_0 = h/2e$ is the superconducting flux quantum. Applying the above equation blindly in our planar junction geometry would mean that $A = L_{\text{eff}} w$, where the effective junction length is $L_{\text{eff}} = L_j + 2\lambda$ [42,66], which is larger than the physical junction length L_j due to the magnetic field penetration into the superconductors by the magnetic penetration depth λ . As can be seen from Eq. (5), the critical current should exhibit nodes with flux period ϕ_0 , giving a magnetic field period $\Delta B = \phi_0/A$.

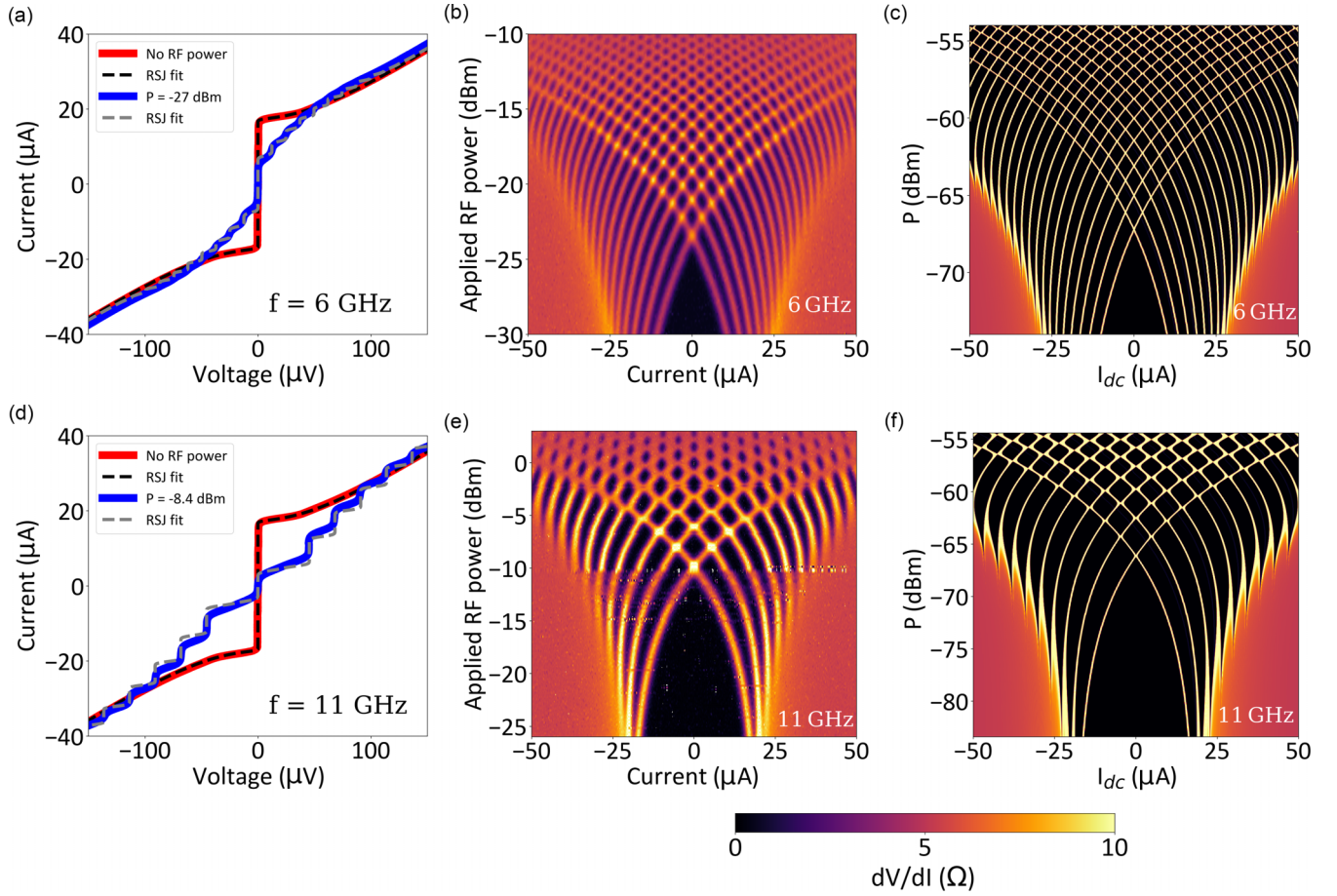


FIG. 6. RF characterization of junction JJ2 at 4.2 K, showing both 6 GHz (a), (b) and 11 GHz (d), (e) measurements and comparison to simulations (c), (f). Panels (a) and (d) show selected IV curves with and without RF power, and theoretical fits using the RSJ model. Panels (b) and (e) show the so-called Shapiro map, i.e., the measured dV/dI as a function of both RF power and dc bias current. As a comparison, Shapiro map simulations are shown in panels (c) and (f). The best-fit parameters were found to be $R_N = 4.8 \Omega$ and $I_c = 17.5 \mu\text{A}$.

However, the above dependence has been shown to be modified in the planar geometry due to flux focusing effects [67], particularly strongly in the thin film limit $t < \lambda$, where nonlocal electrodynamic effects occur [68]. Our films are estimated to satisfy the above thin film condition, as $\lambda \approx 220 \text{ nm}$ has been measured for NbTiN films of similar quality as ours [69], and our thickest film has $t = 100 \text{ nm}$.

Theoretical results for the $I_c(B)$ dependence of planar junctions have been derived in the thin film limit, for junctions narrower than the thin film effective penetration depth (the Pearl length) $\Lambda = 2\lambda^2/t$ and the thin film Josephson penetration depth $\lambda_J^{\text{film}} = \phi_0/(4\pi\mu_0\lambda^2 J_c)$, $w < \Lambda$, $w < \lambda_J^{\text{film}}$ [70–72]. The main result of those studies is that the node spacing of the interference pattern becomes slightly aperiodic, with the details depending on the geometry of the leads, but generally the first node appearing sooner in B than the rest, with the higher node spacings becoming eventually periodic. For the geometry of a long strip corresponding to our samples, Clem [71] gives for the first node position $B_1 = 0.817\Delta B$, where $\Delta B = 1.842\phi_0/w^2$ [67] is the limiting periodicity for the higher-order nodes.

In Fig. 7, we present the results of the magnetotransport measurements for two junctions, JJ2 and JJ4. We focus on junction JJ2 first [Fig. 7(a)], which has a width $w = 2 \mu\text{m}$

and a film thickness $t = 48 \text{ nm}$. The data have been fitted with the simple Fraunhofer model of Eq. (5). Although the film satisfies $t < \lambda$, we see that $I_c(B)$ does not deviate very strongly from the simple Fraunhofer $\sin(x)/x$ modulation, exhibiting an approximately periodicity of the nodes. The

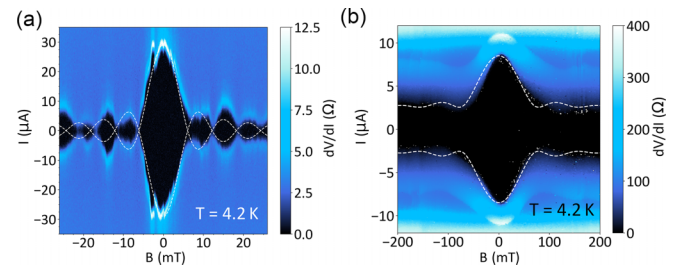


FIG. 7. Panel (a) shows the differential resistance dV/dI of junction JJ2, measured as a function of magnetic field and current I at 4.2 K. I_c is fitted to the Fraunhofer pattern [Eq. (5); white dotted line]. There is clearly a periodic modulation of the critical current as a function of the magnetic field, and the critical current vanishes completely at the nodes. Panel (b) shows the same for junction JJ4, and a fit to Yanson's [Eq. (7)]. In this junction, the modulation as a function of magnetic field is weaker, without full suppression of I_c .

observed period is $\Delta B \approx 5.8$ mT, which is quite different from the theoretical prediction of $\Delta B = 1.842\phi_0/w^2 \sim 1$ mT in the long, narrow, thin film limit [67,71]. However, the heights of the lobes do not decrease monotonically with the applied field, as expected for the ideal case, possibly due to a nonuniform current distribution [66].

To understand the theoretical limits better, we need to estimate the relevant length scales λ , λ_j^{film} and Λ . To estimate λ , we note that even the highest-quality NbTiN films (with similar resistivity $\rho \approx 40 \mu\Omega \text{ cm}$ and $T_c \sim 15\text{--}16$ K as our best films) have been shown to be in the impure limit $l < \xi_0$ [38], where the mean free path l is smaller than the BCS coherence length $\xi_0 = 0.18\hbar v_F/k_B T_c$. In that limit, $\lambda = \lambda_L \sqrt{\xi_0/l}$ [42], which can be rewritten in the limit $T \ll T_c$ with the help of the definitions of the London penetration depth λ_L and Drude resistivity as [73]

$$\lambda \approx 105 \text{ nm} \sqrt{\frac{\rho (\mu\Omega \text{ cm})}{T_c (\text{K})}}. \quad (6)$$

This equation gives for our best films a value $\lambda \approx 150$ nm, close to the measured value in the literature ~ 200 nm. Using that value, we can then estimate for JJ2 $\Lambda \approx 900$ nm and $\lambda_j^{\text{film}} \approx 7.3 \mu\text{m}$. We see that the junction is thin $t < \lambda$, and narrow enough to be in the small junction limit with respect to phase variations $w < \lambda_j^{\text{film}}$, but not with respect to the field variations, i.e., $w > \Lambda$. We thus conclude that it is not totally unexpected that JJ2 does not follow the simplest thin and narrow junction results of Refs. [67,71].

On the other hand, by using the conventional Fraunhofer theory of Eq. (5), seemingly fitting the data better, it is possible to calculate the apparent penetration depth from the observed node spacing $\Delta B = \phi_0/[(L + 2\lambda)w]$. We obtain a value 75 ± 10 nm, which is clearly smaller and inconsistent with the estimates from Eq. (6) and literature in the range $\lambda \approx 150\text{--}200$ nm. Therefore, we conclude that a full understanding of the $I_c(B)$ data from JJ2 would probably require more extensive numerical modeling.

Turning to the second magnetotransport measurement data set for junction JJ4 shown in Fig. 7(b), we note that the junction is much narrower ($w = 300$ nm) and thicker ($t = 100$ nm), barely in the thin film limit $t < \lambda$. The Pearl and Josephson penetration lengths are in this case $\Lambda \approx 450$ nm, and $\lambda_j^{\text{film}} \approx 14.6 \mu\text{m}$, so that JJ4 is closer to the conditions of the limiting theory [67,71], which predicts $\Delta B \approx 42$ mT. That prediction is still roughly a factor of two away from the observed period of ~ 90 mT, but is now much closer than for JJ2.

However, the main noticeable feature in Fig. 5(b) is that the critical current is not fully suppressed at the nodes; i.e., the shape of $I_c(B)$ curve shows an additional constant residual I_c on top of the diffraction pattern. Such a residual I_c has been shown to be caused by random structural inhomogeneities of the barrier, to which Josephson vortices are pinned [42,74]. Yanson [74] showed that the shape of $I_c(B)$ is then altered (in the sandwich-type rectangular junction geometry) to

$$I_c(B) = I_{c0} \sqrt{(1 - \gamma^2)(\sin(X)/X)^2 + \gamma^2}, \quad (7)$$

where $X = \pi BA/\phi_0$. Structural inhomogeneities of the barrier are introduced to this equation by a random spatially fluctuating critical current component $I_1(x)$, $I_c = I_{c0} + I_1(x)$, with its statistical properties defined by the autocorrelation function $\overline{I_1(x_1)I_1(x_2)} = \overline{I_1^2} \exp(-|x_1 - x_2|/r)$, where $\overline{I_1^2}$ is the average square fluctuation amplitude and r is the correlation length. These two parameters combine into the parameter $\gamma^2 = (\overline{I_1^2}/I_{c0}^2) \times (1/\pi N)$ describing the constant background in $I_c(B)$, where $N = w/(2\pi r)$ represents the lateral size of the junction scaled with the correlation length, and Eq. (7) is valid in the limit of small length scale fluctuations $N \gg 1$ and not too large magnetic fields $X \ll N/\pi$. As we see from the above equations, narrow junctions have smaller N and smaller I_{c0} , both of which enhance γ , most likely explaining why the effect of structural disorder is visible in JJ4 but not in JJ2.

When we fitted Eq. (7) to the measured $I_c(B)$ of JJ4, we got a reasonable fit with $\gamma = 0.3$, as shown in Fig. 7(b). We can determine the position of the first minimum, and from this we get $\Delta B \approx 90$ mT, as mentioned before. Yanson's equation predicts the same periodicity as the standard Fraunhofer equation, not taking into account flux focusing and nonlocal electrodynamic effects; therefore, it comes as no surprise that if we calculate the penetration depth for JJ4 from the periodicity, we get a value 40 ± 20 nm inconsistent with the more correct estimate of $\lambda \approx 150$ nm.

V. CONCLUSIONS

In this study, we have shown for the first time a precise local control of superconductivity in NbTiN films using He ion irradiation, and shown that this can be utilized for the fabrication of highly tunable weak links for Josephson junctions. We also characterized the fabricated Josephson junctions extensively using dc, microwave, and magnetotransport measurements, and show that the fabricated junctions are of high quality. Additionally, we demonstrated that we are able to tune the barrier strength and fabricate weak links spanning from the metallic to the insulating limit, with critical current density ranging over five orders of magnitude. The junctions with strongest normal metal barriers have excellent thermal stability; i.e., the critical current depends weakly on temperature at temperatures as high as at 1.5 K, which is quite promising, for example, for high-temperature quantum information and superconducting electronics applications.

In addition, we have pushed the barrier to the insulating side of the superconductor-insulator transition to create SIS junctions. Interestingly, these junctions have relatively low (< 100 meV) tunneling barriers. This is parameter region that is not often reached; thus, other applications for the directly written SIS junctions could result. As NbTiN is also an excellent material for low-loss microwave applications, we see the fabrication of complete Josephson junction quantum devices as a promising direction for this technique, as then only a single superconducting film can be used. This would allow resonators and junctions to be made from the same material, possibly eliminating some of the sources of noise and decoherence associated with extra interfaces and materials. For example, the direct writing method could be used flexibly to fabricate superconducting high-frequency qubits utilizing

either SIS, SNS [75], or constriction [76] junctions. However, one possible difficulty is that the junction critical current density is a strong function of the ion fluence, making the fabrication of SIS junctions in particular a highly sensitive process, as vibrations or beam shifts can influence the junction characteristics. Devices utilizing SNS junctions could perhaps be made in the future more reproducibly and substantially faster with broader beams using heavier ions, such as neon.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [77].

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