Supporting Information for

Direct-Write Printing of Josephson Junctions in a Scanning Electron Microscope

*Tycho J. Blom, Thomas W. Mechielsen, Remko Fermin, Marcel B. S. Hesselberth, Jan Aarts and Kaveh Lahabi**

Kamerlingh Onnes Laboratory, Leiden University, 2300 RA Leiden, the Netherlands.

*Corresponding author: lahabi@physics.leidenuniv.nl

1. Transport in wires made with 80 nA beam current

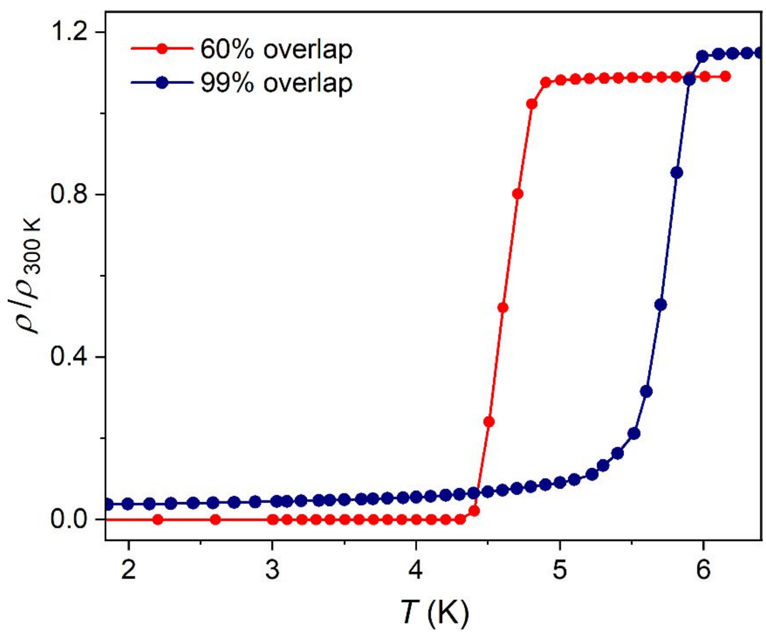

Figure S1. Normalized resistivity *versus* temperature measured for two W-C wires made with 80 nA electron beam current and 25 ms dwell time, using 60% (red) and 99% (blue) beam overlap, corresponding to 43 nm and 1 nm scanning step-size, respectively.

Figure S1 shows the superconducting transition of two W-C wires deposited using a particularly high beam current and a long dwell time (80 nA and 25 ms, respectively). Each wire is made with a different beam overlap. The one with a larger overlap (*i.e.*, smaller pitch/step size) has a higher transition temperature $T_c \approx 5.7$ K; a similar value to the ones reported for W-C wires mad with focused ion beam-induced deposition (*e.g.*, Ga^+). In contrast to the one made with 60% overlap, the wire shows a finite resistance well below its T_c. Extrapolating the resistivity curve to 0 K suggests that the 99% overlap wire might not reach a zero resistance state. The exact origin of the observed residual resistance is not clear at this stage. However, the relative increase in its normal-state resistivity (*i.e.*, lower metallicity compared to the 60% overlap wire) indicates that this may be caused by inhomogeneities in the material.

We find this to be a common trend amongst EBID wires made with large beam currents (20 nA and above). It can be summarized as the following: there is a certain threshold, where the W-C reaches its maximum T_c; increasing the electron beam intensity beyond this limit (*i.e.*, using a higher beam current, overlap or dwell time) would only give rise to unwanted side effects, *e.g.*, broadening of the transition and the appearance of residual resistance. Nevertheless, EBID exhibits the capacity to produce superconducting structures with a quality that can approach ion beam-induced deposition.

2. Inhomogeneous wires

Figure S2 demonstrates the contrast between our EBID Josephson junctions and a W-C wire with a non-uniform superconducting condensate. The wire is deposited by scanning a 20 nA beam in a straight line in 1 nm steps. During the line-scan, we decreased the dwell time over a finite length near the center of the wire. This creates an effective weak spot in the wire, where the condensate is locally suppressed and yields a lower transition temperature, which leads to the observed step in the *R* (*T*) curve (see Figure S2a).

Despite its clear weak spot, the wire shows no sign of Josephson transport and behaves as a single superconducting condensate. In the case of the EBID junctions, we showed that the critical current follows a Gaussian-like decay as a function of an applied magnetic field (vanishing above 35 mT). In contrast, the wire in Figure S2 has a trivial field-dependence; it maintains a constant critical current, which gradually disappears as the field approaches the upper critical field of W-C ($H_{c2} \approx 4$ T). More importantly, the wire does not show a Shapiro response when irradiated with microwaves.

We conclude that a local suppression of the order parameter in a single wire (*e.g.*, by an accidentally formed weak spot) is not sufficient for the formation of two separate condensates, necessary for Josephson transport. Our findings point to the importance of interfaces at the weak link, as they appear to play a crucial role in the amorphous EBID junctions.

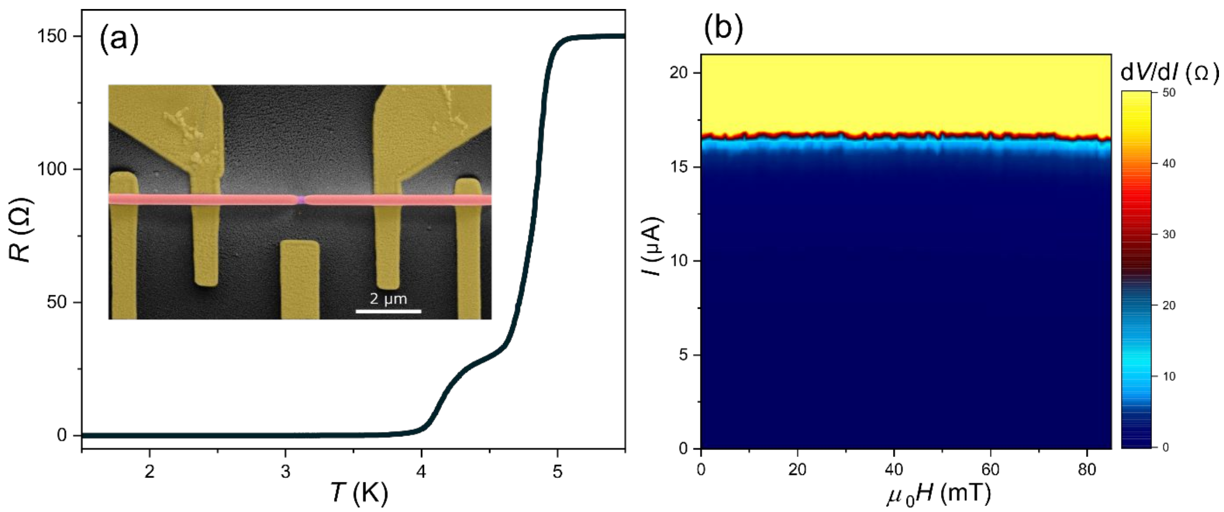

Figure S2. (a) Resistance as a function of temperature *R* (*T*) for an inhomogeneous W-C wire. Inset: false-colored micrograph of the wire (pink). A weak spot is created at the center of the wire, which appears as a slight constriction (colored in purple). The suppression of the order parameter at weak spot manifests itself as the step in the R (T). (b) Colormap of differential resistance (dV/dI) as a function of current bias and applied magnetic field, measured at 1.5 K. As we sweep the field to 80 mT, the critical current shows no change whatsoever.

3. Microwave-induced Shapiro response of device JJ3.

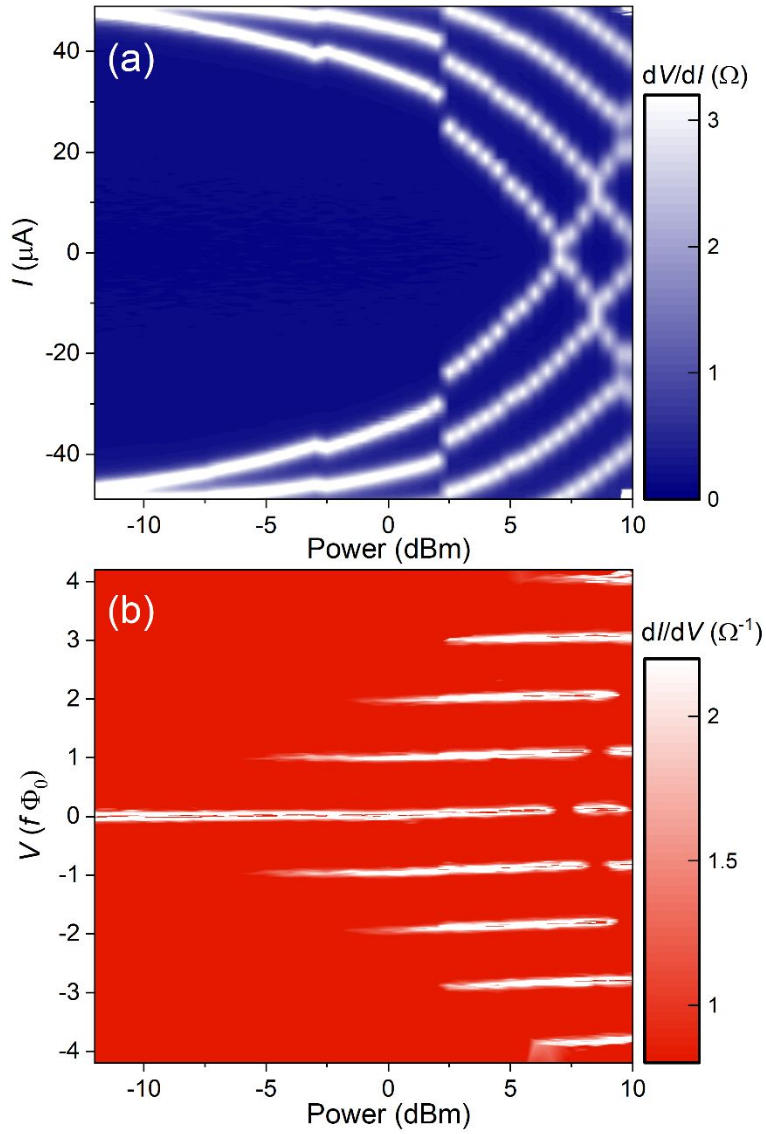

Figure S3. Shapiro response of the Josephson junction JJ3 measured while irradiation with microwave frequency of f = 6.4 GHz at 1.5 K. (a) Differential resistance dV/dI as a function of current bias and RF power. (b) Differential conductance dI/dV plotted as a function of RF power and voltage. To highlight the quantization of the Shapiro response, the voltage scale is normalized in units of $f\Phi_0$, where $\Phi_0 = h/2e$ is the superconducting magnetic flux quantum.

4. Overview of the EBID wires.

	Scan mode /Dimensions	I_{beam} (nA)	τ_{dwell} (ms)	Pitch (nm) /Overlap %	N	Writing time (s)	Total dose	Spot size (nm)
Fig. 1b	Line / 7.7 μm	5.1	25	11 / 60%	40	707	0.47 (μC/μm)	27
	Line / 7.7 μm	10	25	15 / 60%	20	263	0.34 (μC/μm)	37
	Line / 7.7 μm	20	25	23 / 60%	80	678	1.76 (μC/μm)	57
	Line / 7.7 μm	80	25	43 / 60%	80	358	3.72 (μC/μm)	107
Fig. 2a	Raster / (0.2 × 7) μm^2	20	4	23 / 60%	90	1011	14.5 ± 0.6 (μC/μm^2)	57
	Raster / (0.2 × 7) μm^2	20	8	23 / 60%	45	1008	14.5 ± 0.6 (μC/μm^2)	57
	Raster / (0.2 × 7) μm^2	20	10	23 / 60%	35	970	14.5 ± 0.6 (μC/μm^2)	57
	Raster / (0.2 × 7) μm^2	20	15	23 / 60%	25	1043	14.5 ± 0.6 (μC/μm^2)	57
	Raster / (0.2 × 7) μm^2	20	25	23 / 60%	15	1050	14.5 ± 0.6 (μC/μm^2)	57
Fig. 2b	Raster / (0.2 × 7) μm^2	20	4	23 / 60%	40	448	6.4 (μC/μm^2)	57
	Line / 12 μm	20	25	0.8 / 99%	4	1500	2.5 (μC/μm)	57
Fig. S1	Line / 7.7 μm	80	25	43 / 60%	80	358	3.72 (μC/μm)	107
	Line / 7.7 μm	80	25	1 / 99%	2	385	4.00 (μC/μm)	107

Table S1. Summary of the EBID parameters used in the deposition of the W-C wires and ribbons discussed in this work. I_{beam} is the current of the electron beam, τ_{dwell} is the dwell time, N is the number of consecutive scans applied during deposition (*i.e.*, the number times the electron beam scans over a given coordinate), and spot size represents the diameter of the electron beam. The total dose corresponds to (I_{beam}) × (writing time) / (pattern dimensions). For line scans, this is equivalent to ($N \times I_{\text{beam}} \times \tau_{\text{dwell}}$) / (Pitch).