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# Phase Slips and Metastability in Granular Boron-doped Nanocrystalline Diamond Microbridges

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## *BNCD film preparation*

The boron-doped nanocrystalline diamond (BNCD) film was grown on a 2-inch SC-1 cleaned (100) silicon wafer with a 500 nm thick SiO<sub>2</sub> buffer layer using microwave plasma-assisted chemical vapour deposition in a Seki AX6500 series microwave plasma reactor system[1]. Before loading into the reactor chamber, the substrate was seeded for 10 min by ultrasonic agitation in a monodisperse aqueous colloid of nanodiamond particles[2], rinsed in deionised water, and spun dry. The film was grown in a gas mixture of 3% methane in hydrogen. The chamber pressure was 40 Torr, the microwave power was 3.5 kW, and the substrate temperature was 720 °C during growth as measured by a dual wavelength pyrometer. The charge carriers required for superconductivity in diamond were provided by the addition of trimethylboron to the gas mixture with a B/C ratio of 12,800 ppm. If 100% incorporation efficiency from the gas phase is assumed, there is an upper limit of  $2.3 \times 10^{21} \text{ cm}^{-3}$  for the carrier concentration. The film thickness was monitored during growth by *in situ* laser interferometry and subsequently measured by cross sectional scanning electron microscopy (SEM). The surface of the resulting 339 nm thick film is shown in Fig. 1. The film has a distribution of grain sizes, with a mean grain size of 102 nm and a surface

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roughness of  $\sim 25$  nm RMS. Previous work has shown that the surface roughness of the film does not affect the shape and magnitude of the superconducting transition[3].

#### *Microbridge fabrication*

The  $1600 \mu\text{m}$  long microbridges of varying width (4.6, 6.7, and  $10.5 \mu\text{m}$ ) were fabricated from the 339 nm thick BNCD film using a standard top-down photolithographic approach. Microbridge structures were defined by thermal evaporation of a 70 nm nickel mask through patterned resist and subsequent lift-off in acetone. The exposed surrounding BNCD was etched by oxygen inductively coupled plasma reactive ion etching (ICP-RIE). The ICP power was 1500 W, the RIE power was 100 W, and the oxygen flow was 40 sccm. The metal mask was removed in  $\text{FeCl}_3$  and thoroughly cleaned to remove all traces of the mask. The unpatterned sample is an approximately 5 mm square piece of the BNCD sample with the current and voltage leads arranged in a Van der Pauw configuration.

#### *Measurement Techniques*

Four-wire electrical contact to the microbridge samples was made by direct wire bonding to the surface and Ohmic contact behavior was confirmed. Resistance as a function of temperature, shown in Fig. 2, was measured using a Quantum Design Physical Property Measurement System. The excitation current was  $0.5 \mu\text{A}$ , well below both  $I_{c(\text{min})}$  and  $I_{c(\text{max})}$  of all microbridges.

$V(I)$  characteristics were measured at 1.9 K in zero applied field using a bespoke battery-operated voltage-controlled current source and amplifier. The general behavior shown in Fig. 4 persists down to dilution refrigerator temperatures though with a corresponding increase in the achievable  $I_{c(\text{max})}$ . Electromagnetic noise pulses were applied by either operating a small electrical motor close to the electrical measurement apparatus, or by summing the input bias signal with a pulse output by a second computer-controlled arbitrary waveform generator.

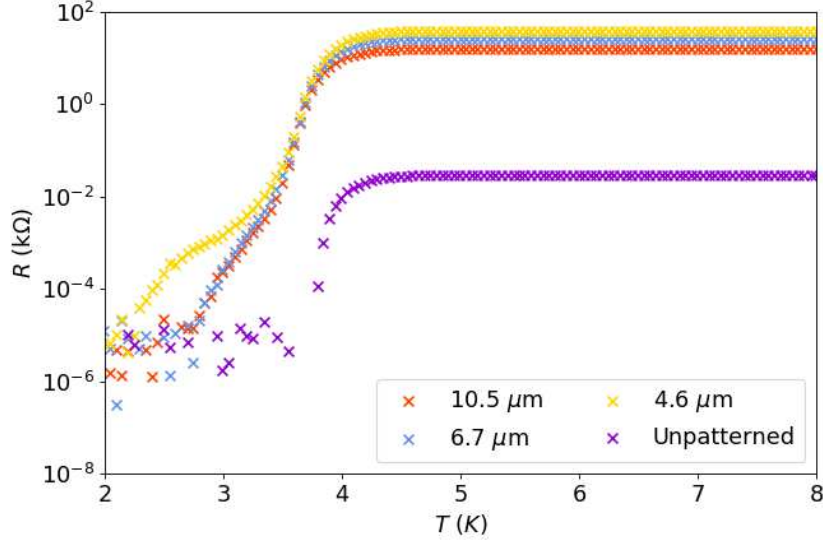


Figure 1: Resistance as a function of temperature,  $R(T)$ , for BNCD microbridges and the unpatterned film shown for the range 2-8 K.

#### *Additional data*

For completeness, the  $R(T)$  and  $V(I)$  graphs for the 4.6 and 10.5  $\mu\text{m}$  microbridges are shown here. Fig. 1 (with detailed fits shown in Fig. 2 and 3) shows all three microbridge  $R(T)$  curves together with that of the unpatterned film; an additional broadening is observed below  $T_c$  for the microbridge samples. This data does show a systematic dependence on bridge width, although it is impossible to make conclusive statements based on only three values of width. The phase slip shoulder in the  $R(T)$  data becomes narrower as bridge width increases, as expected theoretically since the free energy barrier for a phase slip increases with width. Fig. 4 shows  $V(I)$  data for these same microbridges, showing that similar discrete voltage steps are formed. Similarly, the current intercept  $I_0$  in the  $V(I)$  data increases with bridge width, again because the free energy barrier increases with width.

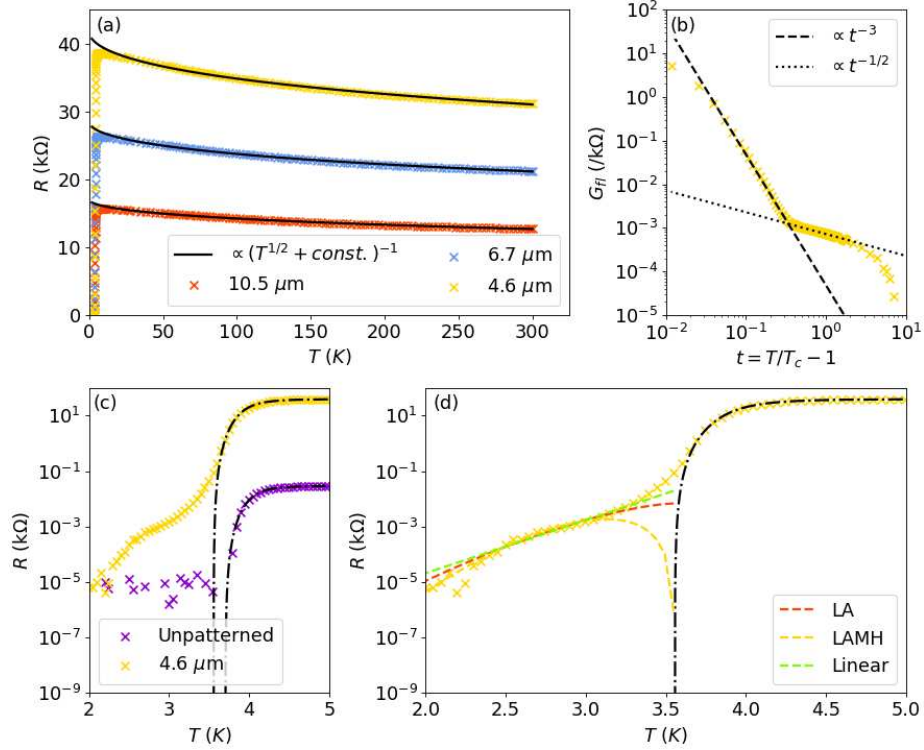


Figure 2: **Resistance as a function of temperature,  $R(T)$ , for BNCD microbridges - focusing on the 4.6  $\mu\text{m}$  wide microbridge - and the unpatterned film.** (a)  $R(T)$  for three 1600  $\mu\text{m}$  long microbridges (widths as indicated by the legend) in the temperature region 2 – 300 K. The high temperature data are fit to the form  $G(T) = a + b\sqrt{T}$  expected from electron-electron interaction theory. (b) Log-log plot of the fluctuation conductivity  $G_{fl}(T)$  as a function of the reduced temperature, showing a crossover from 0D to 3D behavior at  $T - T_c \sim 0.3$  K. (c) The superconducting transition of the unpatterned film does not show evidence of broadening below  $T_c$ . The black line is a fit to the fluctuation conductivity. The superconducting transition of the 4.6  $\mu\text{m}$  wide microbridge is shown for comparison. (d) Low temperature  $R(T)$  for the 4.6  $\mu\text{m}$  wide microbridge. The resistance below  $T_c$  is fit to the LA (red), LAMH (yellow) and linear (green) forms. Note that none of these are expected to be accurate close to  $T_c$  as they assume large free energy barriers.

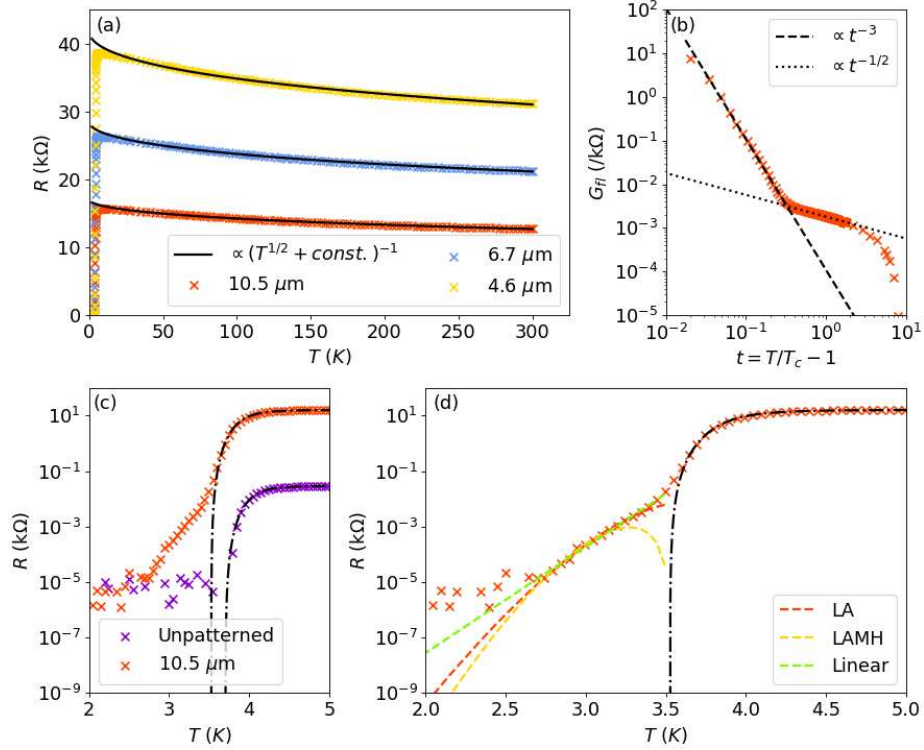


Figure 3: **Resistance as a function of temperature,  $R(T)$ , for BNCD microbridges - focusing on the 10.5  $\mu\text{m}$  wide microbridge - and the unpatterned film.** (a)  $R(T)$  for three 1600  $\mu\text{m}$  long microbridges (widths as indicated by the legend) in the temperature region 2 – 300 K. The high temperature data are fit to the form  $G(T) = a + b\sqrt{T}$  expected from electron-electron interaction theory. (b) Log-log plot of the fluctuation conductivity  $G_{fl}(T)$  as a function of the reduced temperature, showing a crossover from 0D to 3D behavior at  $T - T_c \sim 0.3$  K. (c) The superconducting transition of the unpatterned film does not show evidence of broadening below  $T_c$ . The black line is a fit to the fluctuation conductivity. The superconducting transition of the 10.5  $\mu\text{m}$  wide microbridge is shown for comparison. (d) Low temperature  $R(T)$  for the 10.5  $\mu\text{m}$  wide microbridge. The resistance below  $T_c$  is fit to the LA (red), LAMH (yellow) and linear (green) forms. Note that none of these are expected to be accurate close to  $T_c$  as they assume large free energy barriers.

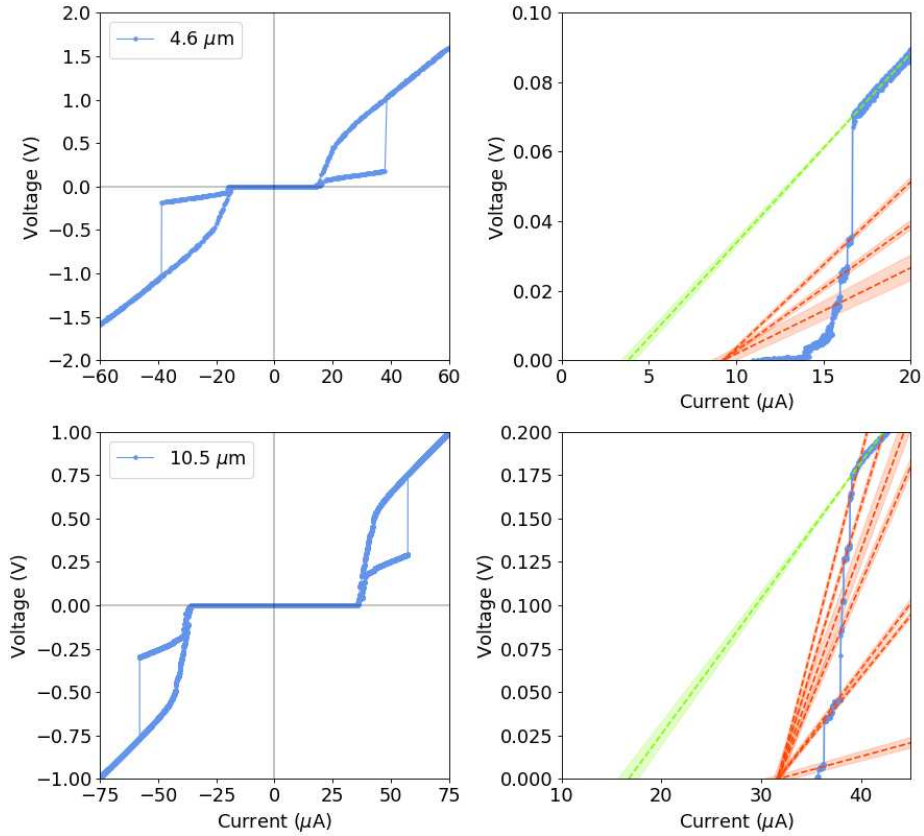


Figure 4: **Current-biased  $V(I)$  characteristics for the  $4.6\ \mu\text{m}$  wide (top) and  $10.5\ \mu\text{m}$  wide (bottom) microbridges.** A detailed view of individual voltage steps for each sample, showing the converging linear slopes, is shown next to the full  $V(I)$  characteristic for each sample. As with the  $6.7\ \mu\text{m}$  wide microbridge, there are two points of intercept on the current axis, where the lower intercept is around half of the upper.

## References

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