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## Superconducting tantalum nitride-based normal metal-insulator-superconductor tunnel junctions

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# Superconducting tantalum nitride-based normal metal-insulator-superconductor tunnel junctions

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We report the development of superconducting tantalum nitride ( $\text{TaN}_x$ ) normal metal-insulator-superconductor (NIS) tunnel junctions. For the insulating barrier, we used both  $\text{AlO}_x$  and  $\text{TaO}_x$  ( $\text{Cu-AlO}_x\text{-Al-TaN}_x$  and  $\text{Cu-TaO}_x\text{-TaN}_x$ ), with both devices exhibiting temperature dependent current-voltage characteristics which follow the simple one-particle tunneling model. The superconducting gap follows a BCS type temperature dependence, rendering these devices suitable for sensitive thermometry and bolometry from the superconducting transition temperature  $T_C$  of the  $\text{TaN}_x$  film at  $\sim 5$  K down to  $\sim 0.5$  K. Numerical simulations were also performed to predict how junction parameters should be tuned to achieve electronic cooling at temperatures above 1 K. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4869563>]

Normal metal-insulator-superconductor (NIS) tunnel junction devices aimed at low temperature thermometry, bolometry, and refrigeration have witnessed significant developments in the last decade.<sup>1,2</sup> Aluminum (Al) based NIS devices already offer sensitive thermometry in the sub 1 K range,<sup>3</sup> and significant cooling power approaching 1 nW at  $\sim 0.3$  K has recently been demonstrated.<sup>4,5</sup> In addition to direct electronic cooling, sizeable indirect phonon cooling of suspended membranes,<sup>6–8</sup> beams,<sup>9</sup> and a general-purpose refrigeration platform<sup>4</sup> have been achieved using Al coolers. However, to achieve operation at higher temperatures, one must switch to materials with higher superconducting transition temperatures ( $T_C$ ) than the  $T_C$  of Al at  $\sim 1.2$  K, as  $T_C$  limits the maximum range of thermometry, and cooling power drops strongly above  $T \sim 0.4T_C$ .<sup>1</sup>

Recently, we fabricated Nb ( $T_C \sim 8$  K)<sup>10</sup> and  $\text{NbN}_x$  ( $T_C \sim 12$  K)<sup>11</sup> based NIS devices and demonstrated an order of magnitude increase of the thermometry range, and an observation of some electronic cooling in the Nb device.<sup>10</sup> However, as the optimal operational temperature for cooling for those type of devices is around 3.5–5 K, one should also develop NIS devices with a  $T_C$  in the intermediate range between Al and Nb/ $\text{NbN}$  devices. This is important because the cooling power also deteriorates fast when the operational temperature is lower than the optimal, and thus Nb or  $\text{NbN}$  based coolers may not be able to work effectively enough in the temperature range 1–3 K. Here, we experimentally demonstrate that tantalum nitride (Ta<sub>N</sub>) with a  $T_C \sim 5$  K can be used as the superconducting electrode in a micron-scale NIS device. The thermometric characteristics were essentially ideal in the temperature range 0.5–5 K, and the observed specific tunneling resistance and the broadening of the superconducting density of states (DOS) were reasonably low, giving us hope of also developing electronic coolers in the temperature range 1–3 K in the future. This was elaborated by numerical simulations, which demonstrated that a further lowering of the specific tunneling resistance of the junctions (in principle a straightforward process) would lead to a

sizeable electronic cooling at temperatures around 1.5–3 K, despite the observed broadening of the superconducting density of states being higher than for typical Al junctions. In addition, if the broadening could be reduced to levels commonly seen for Al, a truly wonderful device capable of reducing temperature from 1.2 K to 0.2 K would follow.

Tantalum nitride ( $\text{TaN}_x$ ) is a material whose  $T_C$  has been shown to be tunable in thin films between 4 and 10.8 K by adjusting the growth parameters.<sup>12–15</sup> Moreover, depending upon the amount of incorporated nitrogen  $x$ ,  $\text{TaN}_x$  can be a superconductor, insulator, or a metal at low temperatures.<sup>12,16,17</sup> In superconducting device applications, however, TaN has not been used widely. In its normal state, it has been used as a barrier material in superconductor-normal metal-superconductor (SNS) Josephson junctions with NbN (Refs. 18–20) and NbTiN (Ref. 21) as the superconducting electrode materials. As a superconductor, the only device application so far has been for superconducting single photon detection,<sup>22</sup> and notably, no tunnel junction devices have been reported before. Recently, we were able to grow high quality  $\text{TaN}_x$  thin films with  $T_C$  up to  $\sim 8$  K using a pulsed laser deposition (PLD) technique.<sup>13</sup> Furthermore, we have already fabricated  $\text{NbN}_x$  based NIS junctions, using PLD for the growth of  $\text{NbN}_x$  films, and electron beam lithography (EBL), reactive ion etching (RIE), and shadow angle evaporation for the device fabrication, with an *ex-situ* thermally oxidized Al barrier.<sup>11</sup> These two advances were combined here to develop  $\text{Cu-AlO}_x\text{-Al-TaN}_x$  NIS tunnel junctions.

First, 30 nm thick superconducting  $\text{TaN}_x$  films with  $T_C$  in the range  $\sim 4.5$ –5 K were deposited on (100) oriented MgO single crystals using a PLD technique described in detail elsewhere.<sup>13</sup> A typical temperature dependence of the resistance of such a bare  $\text{TaN}_x$  film is shown in Figure 1(a). MgO was chosen as the substrate because the films grown on it were shown to be monophasic superconducting FCC (rocksalt), while in the films grown on oxidized silicon a coexisting non-superconducting hexagonal phase was also found.<sup>13</sup>

The  $\text{TaN}_x$  films were patterned into 1  $\mu\text{m}$  wide electrodes and large contact pads by EBL and RIE. To make a more

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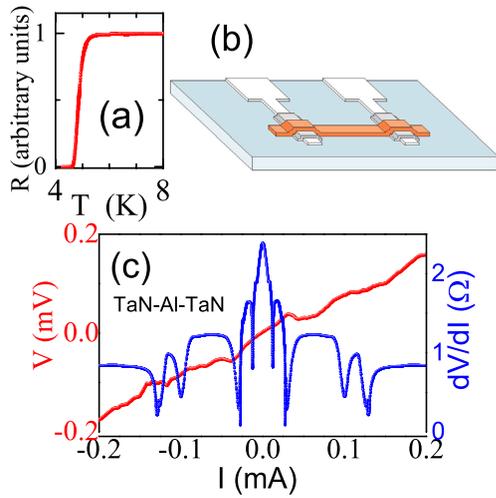


FIG. 1. Temperature dependence of the resistance of the bare  $\text{Ta}_x\text{N}_x$  film, used for fabricating the  $\text{Ta}_x\text{N}_x\text{-Al-AIO}_x\text{-Cu}$  device, exhibiting superconducting transition at  $\sim 5\text{K}$ . The ac bias current used was  $10\ \mu\text{A}$ . (b) A schematic of a fabricated device with two junctions. Blue: MgO substrate, White: TaN electrodes, Grey: Al/AIO<sub>x</sub> film, and Orange: Cu wire. (c) Bias current dependence of the voltage and differential resistance of a  $\text{Ta}_x\text{N}_x\text{-Al-TaN}_x$  SNS junction at 4.2 K.

resistant etch mask, the  $\text{Ta}_x\text{N}_x$  was first covered with a 50 nm thick evaporated Cu film, on top of which a 400 nm thick positive PMMA resist was spun, followed by EBL electrode patterning and removal of the Cu in the exposed regions with a chemical etch (30%  $\text{H}_2\text{O}_2$ , glacial acetic acid, DI water 1:1:18). After that, the exposed  $\text{Ta}_x\text{N}_x$  was etched by RIE using  $\text{CHF}_3$ , 50 sccm and  $\text{O}_2$ , 5 sccm at a power 100 W and pressure 55 mTorr, the PMMA removed, and finally the remaining Cu removed by another chemical etch step.

The electrode patterning was followed by the fabrication of three distinct types of devices using a second overlay EBL step and ultra-high vacuum (UHV) e-beam evaporation. For the first device type, a 40 nm thick,  $0.5\ \mu\text{m}$  wide, and  $15\ \mu\text{m}$  long aluminum cross strip was deposited across the electrodes, without any explicit attempt to form tunnel barriers. The purpose of this sample is to determine the quality of the  $\text{Al-Ta}_x\text{N}_x$  contact, as an unwanted native oxide barrier may exist on the surface of the  $\text{Ta}_x\text{N}_x$  film. For the second device type, the method previously developed for the  $\text{Nb}_x\text{N}_x$  NIS junction fabrication with  $\text{AlO}_x$  tunnel barriers has been used.<sup>11</sup> First, 40 nm thick Al islands of size  $6\ \mu\text{m} \times 6\ \mu\text{m}$  were evaporated on top the  $\text{Ta}_x\text{N}_x$  electrodes, followed by *in-situ* oxidation at room temperature in 50 millibars of  $\text{O}_2$  for 4 min, to grow the  $\text{AlO}_x$  tunnel barriers. Then, without breaking the vacuum, a 100 nm thick Cu strip of width  $0.5\ \mu\text{m}$  was evaporated to form the connection between two  $\text{Ta}_x\text{N}_x$  electrodes (separated by a distance of  $15\ \mu\text{m}$ ) so that a series connection of two  $\text{Cu-AIO}_x\text{-Al-Ta}_x\text{N}_x$  NIS tunnel junctions (SINIS) is formed [Fig. 1(b)]. The third device type was identical with the second, except that no Al was deposited, and the  $\text{Ta}_x\text{N}_x$  electrodes were directly oxidized in 400 millibars of  $\text{O}_2$  for 30 min. The goal of this process is a SINIS device with a  $\text{Cu-TaO}_x\text{-Ta}_x\text{N}_x$  tunnel junction structure. The typical junction dimensions were  $\sim 1 \times 0.5\ \mu\text{m}^2$ .

Since the  $\text{Ta}_x\text{N}_x$  films come in contact with ambient atmosphere for prolonged periods of time during the process of fabrication, we investigated the effects of a possible native oxide barrier with the help of the first type of  $\text{Ta}_x\text{N}_x\text{-Al-Ta}_x\text{N}_x$

device. The measured voltage and differential resistance vs. current characteristics at 4.2 K are shown Figure 1(c). Clearly, the data shows that the contact resistance is low  $< 1\ \Omega/\text{junction}$  (four orders of magnitude less than the tunneling resistances of the second and third type devices, as will be shown later), and that the general behavior is that of a good NS contact, although several resonance features are seen, possibly originating from multiple Andreev reflections.<sup>23</sup> The resonance features were not observed in similar devices using NbN electrodes,<sup>11</sup> however, the NS contact resistance in NbN devices was actually orders of magnitude higher for unknown reasons.

The current-voltage and conductance-voltage measurements for the second and third type devices were carried out using a  $\text{He}^3\text{-He}^4$  dilution refrigerator. The measurement lines had three stages of filtering: pi-filters at 4.2 K, RC-filters at the base temperature, and microwave filtering<sup>24</sup> between these two (Thermocoax cables of length 1.5 m). For the measurement of conductance, a lock-in technique with a 0.04 mV excitation voltage and 17 Hz frequency was used. In Figure 2, the current-voltage ( $I$ - $V$ ) characteristics at various bath temperatures  $T_{\text{Bath}}$  for a  $\text{Ta}_x\text{N}_x\text{-Al-AIO}_x\text{-Cu}$  based double junction SINIS device are shown in (a) log-linear and (b) linear scales, respectively, together with the corresponding theoretical fits based on the single-particle tunneling model  $\frac{1}{eR_T} \int_{-\infty}^{\infty} d\epsilon N_S(\epsilon) (f_N(\epsilon - eV) - f_N(\epsilon + eV))$ , where  $f_N(\epsilon)$  is the Fermi function in Cu wire, and  $N_S(\epsilon)$  is the normalized broadened superconducting quasiparticle DOS in the Dynes

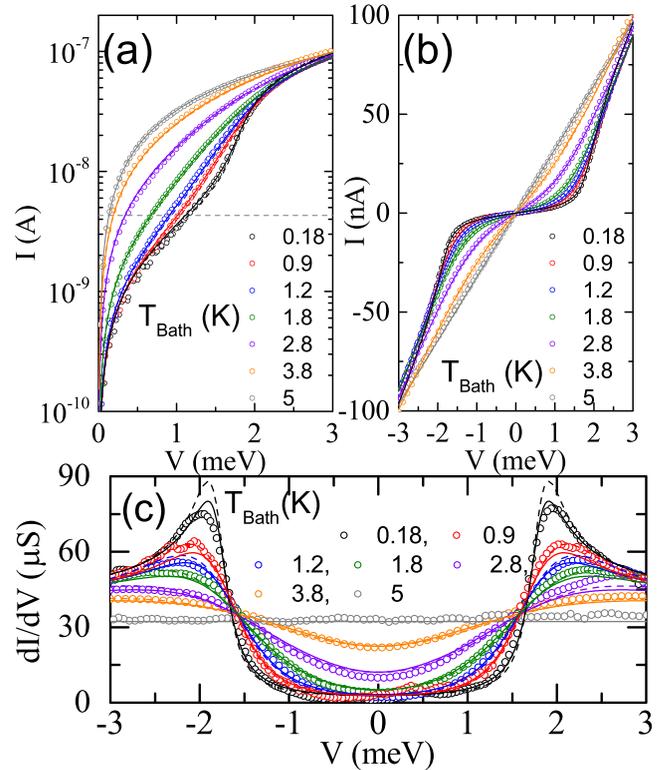


FIG. 2. Temperature dependence of the current-voltage characteristics of a double junction based  $\text{Cu-AIO}_x\text{-Al-Ta}_x\text{N}_x$  device at various  $T_{\text{Bath}}$  plotted in (a) log-linear and (b) linear scale. (c) Differential conductance characteristics corresponding to plots in (a). The open symbols denote the measured response, while the lines are the corresponding theoretical fits. The dashed and solid lines corresponds to calculations where the tunnelling resistance of individual junctions are assumed to be equal and unequal (proportions 66% and 34%), respectively. The fitting parameters were  $\Gamma/\Delta(0) = 7 \times 10^{-2}$  and  $R_T$ . The horizontal dashed line in (a) represents a constant current bias of 4.3 nA.

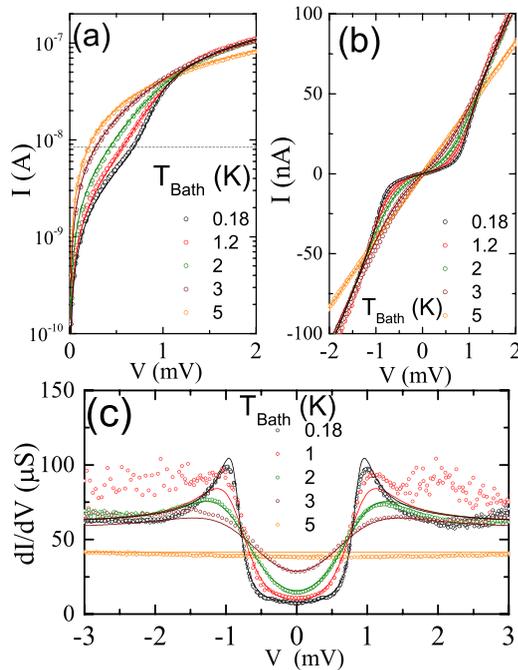


FIG. 3. Temperature dependence of the current-voltage characteristics of a single junction based Cu-TaO<sub>x</sub>-TaN<sub>x</sub> device at various  $T_{\text{Bath}}$  plotted in (a) log and (b) linear scale. (c) Differential conductance characteristics corresponding to plots in (a). The dots are the experimental data, while the solid lines are the corresponding theoretical fits. The fitting parameters were  $\Gamma/\Delta(0) = 0.13$  and  $R_T$ . The horizontal dashed line in (a) represents a constant current bias of 8.4 nA.

model<sup>1,25</sup>  $N_S(\epsilon, T_S) = \left| \text{Re} \left( \frac{\epsilon + i\Gamma}{\sqrt{(\epsilon + i\Gamma)^2 - \Delta^2}} \right) \right|$ , where  $\Gamma$  is the parameter describing broadening and  $\Delta$  is the superconducting gap. The corresponding conductance characteristics along with the theoretical fits are shown in Figure 2(c). For all these fits both the superconductor and normal metal temperatures  $T_S$  and  $T_N$  were set equal to  $T_{\text{Bath}}$ . The dashed lines (most clearly visible for the lowest temperature data in (a) and (c)) assume that the tunneling resistances of the individual junctions are identical, while the solid lines assume non-identical tunneling resistances<sup>26</sup> with proportions 66% and 34% of the total resistance. This asymmetry was directly measured with the help of a third NIS junction connected to the same normal metal electrode. The individual junction resistances can then be solved from the three measurements of the SINIS pairs. The agreement between the data and the simplest possible theory with two identical barriers is already very good at higher temperatures, where the effect of the asymmetry is weaker. However, at 0.18 K, the symmetric model predicts a lower sub-gap current (visible at  $V \sim 1.5$  mV) than what is observed, and the non-symmetric theory can explain this increase. It is quite important to take into account the asymmetry at low  $T$ : Simply fitting to the subgap conductance with  $T_N$  as a free parameter would give  $T_N \sim 0.5$  K. Such a high electronic overheating is unphysical, as it would require an excess heating power  $>100$  pW (much higher than  $\sim 10$  fW typically seen in our setup<sup>9</sup>), as estimated from the known electron-phonon interaction constant for Cu (Ref. 27) and the size of the normal metal island. The physical mechanism for the observed variability in  $R_T$  is unclear, although it has been suggested<sup>28</sup> that it could result from grain-to-grain barrier variability.

From the fits, we also get the temperature dependence of the superconducting gap  $\Delta$ , which was seen to follow the simple BCS theory well, in contrast to the NbN<sub>x</sub> based devices<sup>11</sup> which exhibited stronger modifications due to proximity effect.<sup>29</sup> At 0.18 K, the measured  $\Delta$  was  $\sim 0.9$  meV, about four times higher than a typical Al film gap, indicating that the Al layer is well proximized by the TaN<sub>x</sub>. This value of  $\Delta$  is almost the same as in the NbN NIS devices<sup>11</sup> although  $T_C = 5$  K is less than half, an observation which is consistent with the fact that the contact resistance between TaN<sub>x</sub> and Al is much lower. All the theory fits to the  $I - V$  and conductance curves were obtained with a broadening parameter  $\Gamma/\Delta(0) = 7 \times 10^{-2}$  [ $\Delta(0) = \Delta(T=0)$ ], a value which is slightly higher than the smallest value observed in the NbN<sub>x</sub> devices,  $\Gamma_{\text{NbN}}/\Delta_{\text{NbN}} = 2.4 \times 10^{-2}$ . Similar to the NbN case, strong coupling theory did not fit the data well (not shown). Finally, the total  $R_T$  of this device was, surprisingly, found to evolve with temperature, from  $\sim 31$  k $\Omega$  at 5 K to  $\sim 26.5$  k $\Omega$  at 3.8 K and  $\sim 24.5$  k $\Omega$  at still lower temperatures. This translates to a specific junction resistance  $r_S$  of  $\sim 6.5$  k $\Omega \mu\text{m}^2$ , which is about two orders of magnitude smaller than that in the NbN<sub>x</sub> devices fabricated in a similar manner, but still about three-ten times higher than that of typical high power Cu-AIO<sub>x</sub>-Al tunnel junction coolers.<sup>4,5</sup>

For the devices of the third type (Ta<sub>x</sub>N<sub>x</sub>-TaO<sub>x</sub>-Cu), the yield was quite low—most of them were shorts. However, some were tunnel junctions. In Figures 3(a) and 3(b), the current-voltage ( $I - V$ ) characteristics at various  $T_{\text{Bath}}$  of such a Ta<sub>x</sub>N<sub>x</sub>-TaO<sub>x</sub>-Cu *single* NIS junction are shown in (a) log-linear and (b) linear scale, respectively, together with the corresponding theoretical fits. The measured and theoretical conductance curves are shown in Figure 3(c). From the theoretical fits, the obtained value of  $\Gamma/\Delta(0)$  and  $\Delta(0)$  were 0.13 and 0.87 meV, respectively, with  $T_C = 4.5$  K being the measured value of the Ta<sub>x</sub>N<sub>x</sub> film. Here, the obtained value of  $R_T$  evolved with temperature even more strongly, from  $\sim 24$  k $\Omega$  at 5 K to  $\sim 16.5$  k $\Omega$  below 5 K. The origin of this temperature dependence of  $R_T$  is unclear to us at the moment. The largest change seems to be correlated with the transition to the superconducting state, but some temperature dependence seems to be left even at temperatures much below  $T_C$ . Although the  $\Delta$  values of Ta<sub>x</sub>N<sub>x</sub>-TaO<sub>x</sub>-Cu and Ta<sub>x</sub>N<sub>x</sub>-Al-AIO<sub>x</sub>-Cu junctions are almost identical, the low yield and the larger value of  $\Gamma$  of the latter render them unfit for real device applications.

Figure 4 shows the thermometric response in the usual measurement configuration where the NIS junction device is current biased, and its voltage ( $V$ ) response is measured as a function of  $T_{\text{Bath}}$ , of the (a) double junction Ta<sub>x</sub>N<sub>x</sub>-Al-AIO<sub>x</sub>-Cu device and (b) single junction Ta<sub>x</sub>N<sub>x</sub>-TaO<sub>x</sub>-Cu device. For both devices, the measured temperature sensitivity was  $\sim 0.14$  mV/K/junction from  $T_C$  down to  $\sim 0.5$  K, as expected from theory, but at the lowest temperatures there is a saturation and even a curious downturn of the voltage. This downturn cannot be explained by any theory where  $R_T$  is temperature independent for such low bias (sub-gap) values,<sup>26</sup> and thus the thermometry data confirms the picture of changing  $R_T$ , as can be seen from the representative theory curves.

Having obtained the values for  $\Gamma$  and  $r_S$  for the Ta<sub>x</sub>N<sub>x</sub> NIS devices, we should compare them with previous results using other superconductors. In Table I, we have compiled

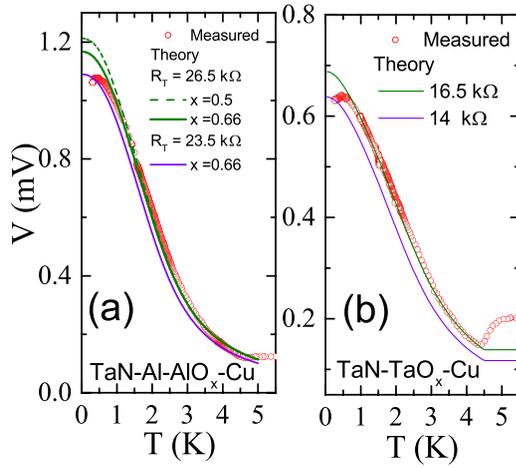


FIG. 4. Thermometry characteristics of the (a) Cu-AlO<sub>x</sub>-Al-TaN<sub>x</sub> junction pair biased with a constant current of  $\sim 4.3$  nA and (b) a single Cu-TaO<sub>x</sub>-TaN<sub>x</sub> junction biased with  $\sim 8.4$  nA. The dots are the experimental data, while the lines indicate the corresponding theoretical fits, assuming a simple one particle tunnelling model with BCS temperature dependence of the superconducting gap, for various cases of  $R_T$ . In (a), dashed line, symmetric  $R_T = 26.5$  k $\Omega$ , solid green line, asymmetric  $R_T = 26.5$  k $\Omega$  with proportions 66% and 34% of the two junction resistances, solid purple line,  $R_T = 23.5$  k $\Omega$ , same asymmetry. In (b), solid green line,  $R_T = 16.5$  k $\Omega$ , solid purple line,  $R_T = 14$  k $\Omega$ .

results from our lab, fabricated in the same chamber and with fairly similar oxidation parameters. The parameters for TaN<sub>x</sub>-Al-AIO<sub>x</sub>-Cu junctions seem to be comparable to the earlier results for Nb-Al-AIO<sub>x</sub>-Cu junctions. The biggest difference to the standard Al-AIO<sub>x</sub>-Cu junction technology is the much larger value of the broadening parameter  $\Gamma$ . The NbN junctions do not seem as promising for cooling as TaN junctions due to the high specific junction resistances. The DOS broadening seen in our Al-AIO<sub>x</sub>-Cu junctions is comparable to the results by other labs.<sup>28,30,31</sup> However, if extreme measures are taken to reduce environmental radiation coupling to the junction, much lower broadening has been demonstrated in Al-AIO<sub>x</sub>-Cu junctions,<sup>30,32</sup> explained by photon-assisted tunneling. According to that picture  $\Gamma/\Delta \sim 1/\Delta$ , which suggests that the broadening in our higher gap junctions (Nb,NbN,TaN) is due to some other mechanism.

Finally, to answer better whether TaN based NIS junctions hold promise for cooling applications, we also carried out some numerical simulations. To give an example, all calculations assumed a SINIS device with  $T_C = 5$  K and  $\Delta = 0.9$  meV, and a Cu normal metal island of thickness

TABLE I. Broadening of the density of states  $\Gamma/\Delta(0)$ , specific tunneling resistance  $r_S$ , energy gap at low temperature  $\Delta(0)$ , and critical temperature  $T_C$  for various types of junctions. All these junctions were oxidized in the same physical chamber under fairly identical oxidation conditions.

Junction	$\frac{\Gamma}{\Delta(0)}$	$r_S$ (k $\Omega \mu\text{m}^2$ )	$\Delta(0)$ (meV)	$T_C$ (K)	References
Al-AIO <sub>x</sub> -Cu	$1-5 \times 10^{-4}$	1-2	0.21	1.4	9
Nb-Al-AIO <sub>x</sub> -Cu	$5 \times 10^{-2}$	10	1.0	6	10
NbN <sub>x</sub> -Al-AIO <sub>x</sub> -Cu	$2-4 \times 10^{-2}$	630-770	1.1	10.8	11
NbN <sub>x</sub> -NbO <sub>x</sub> -Cu	0.2	40	1.1	10.8	11
TaN <sub>x</sub> -Al-AIO <sub>x</sub> -Cu	$7 \times 10^{-2}$	6.5	0.9	5	
TaN <sub>x</sub> -TaO <sub>x</sub> -Cu	0.13	8	0.9	4.5	

30 nm, with a lateral size the same as the total junction area  $A$ . Electron-phonon interaction limited heat flow out of the island was also assumed, which is the typical situation for junctions on bulk substrates,<sup>2,9</sup> leading to heat balance  $P_{cool} = \Sigma\Omega(T_{bath}^5 - T_N^5)$ , where  $P_{cool}$  is the cooling power of the junctions that can be calculated when junction parameters are known,<sup>2,9</sup>  $\Omega$  is the normal metal volume, and  $\Sigma$  is the electron-phonon coupling constant. A typical value for  $\Sigma = 2 \times 10^9$  W/(m<sup>3</sup>K<sup>5</sup>) in Cu was used.<sup>27</sup> Since  $P_{cool} \propto A$  and  $\Omega \propto A$ , the results shown here are independent of  $A$ , and therefore we use the specific junction resistance  $r_S$  as parameter. In Figure 5(a), we show the expected decrease of  $T_N$  below  $T_{Bath}$ , as a function of  $\Gamma$  and  $T_{Bath}$  for the value of specific junction resistance observed in the experiment  $r_S = 6.5$  k $\Omega \mu\text{m}^2$ . We find that a bit of cooling is expected at low  $T_{Bath} \sim 0.2-0.3$  K if  $\Gamma/\Delta(0)$  could be lowered to values  $< 10^{-3}$ . However, at that temperature range Al coolers perform better. On the other hand, if the value of  $r_S$  is lowered, as shown in Fig. 5(b), but  $\Gamma/\Delta(0)$  is fixed at the observed value  $7 \times 10^{-2}$ , a fair amount of cooling (up to 0.3 K) at high  $T_{Bath} \sim 2-3$  K is possible when  $r_S < 10$   $\Omega \mu\text{m}^2$ . Even this would fall far short from the ultimate goal to cool the metal island from 1.2 K to 0.3 K. In order to achieve such a large magnitude in cooling, a concomitant reduction in  $\Gamma/\Delta(0)$  of these TaN<sub>x</sub> devices is also necessary. As shown in Fig. 5(c), if  $\Gamma/\Delta(0)$  could be lowered to  $1 \times 10^{-4}$  (typical for Al devices), then for  $r_S < 100$   $\Omega \mu\text{m}^2$  such a large cooling would be theoretically possible. Interestingly, these kind of values for  $\Gamma$  and  $r_S$  have been obtained experimentally for Al-AIO<sub>x</sub>-Cu junctions.

In conclusion, we have demonstrated the application potential of normal metal-insulator-superconductor tunnel junction devices with TaN as the superconductor. The electrical characteristics of these devices follow the simple one-particle tunneling model, and the superconducting gap exhibit a BCS type temperature dependence. We also demonstrated sensitive thermometry between 0.5 and 5 K, where the lower limit was shown to be caused by an unexpected

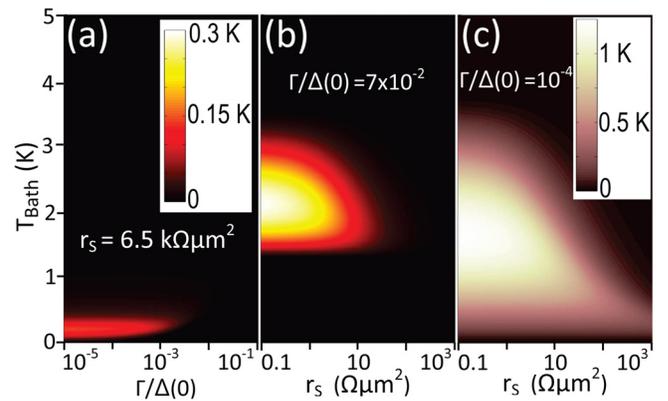


FIG. 5. Calculated electronic cooling ( $T_{Bath} - T_N$ ) for several cases, with electron-phonon limited heat transport and Cu as normal metal. Only regions where net cooling occur ( $T_{Bath} \geq T_N$ ) are shown. (a) Cooling as a function of  $T_{Bath}$  and  $\Gamma/\Delta(0)$  for  $r_S = 6.5$  k $\Omega \mu\text{m}^2$ . In (b) and (c), calculated cooling as a function of  $T_{Bath}$  and  $r_S$  for (b)  $\Gamma/\Delta(0) = 7 \times 10^{-2}$  and (c)  $\Gamma/\Delta(0) = 1 \times 10^{-4}$ . The color bars indicate the magnitude of cooling. The color bar in the inset of (a) serves as the scale for both (a) and (b). It can be seen from (c) that for a device with  $\Gamma/\Delta(0) = 1 \times 10^{-4}$  and  $r_S \sim 10$   $\Omega \mu\text{m}^2$ , the expected cooling at 1.2 K is  $\sim 1$  K. For all simulations  $T_C = 5$  K and  $\Delta = 0.9$  meV.

temperature variability of the tunneling resistance. The measured effective broadening of the superconducting density of states and the specific tunneling resistance of these devices were just high enough to inhibit any electronic cooling. However, as we showed theoretically, a realistic reduction of these parameters for TaN devices would lead to a dramatic breakthrough in the development of practical electronic coolers for 1 K temperature range. Future efforts need to be especially focused on understanding the broadening of the superconducting density of states and how to reduce it.

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