Tunneling study of cavity grade Nb: possible magnetic scattering at the surface

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Tunneling spectroscopy was performed on Nb pieces prepared by the same processes used to etch and clean superconducting radio frequency (SRF) cavities. Air exposed, electropolished Nb exhibited a surface superconducting gap Δ=1.55 meV, characteristic of clean, bulk Nb. However the tunneling density of states (DOS) was broadened significantly. The Nb pieces treated with the same mild baking used to improve the Q-slope in SRF cavities, reveal a sharper DOS. Good fits to the DOS were obtained using Shiba theory, suggesting that magnetic scattering of quasiparticles is the origin of the gapless surface superconductivity and a heretofore unrecognized contributor to the Q-slope problem of Nb SRF cavities.

Elemental niobium (Nb) is the material of choice in two of the most important commercial superconducting devices: i) the Josephson tunnel junction (JTJ) and ii) the superconducting radio frequency (SRF) cavity. The complex surface oxides of air-exposed Nb5 have played an important role in the development of both devices over the past 30 years. For JTJs the deleterious effects of the surface oxides (reduced gaps and Josephson currents, large sub-gap quasiparticle currents, etc.) were eliminated by introducing an ultra-thin capping layer of Al, a technique first successfully established on Nb foils5. Prevention of oxygen exposure to the underlying Nb is the key to the construction of JTJ devices such as mixers and analog-digital converters, all of which now utilize Nb/Al bi-layer technology6.

For SRF cavities the Nb oxide layers are relevant because they occupy a significant fraction of the region where electric and magnetic fields E and B are confined, within one magnetic penetration depth (~45 nm) from the surface. The reduction of the SRF cavity quality factor Q with increasing E field, (Q-slope problem) and its mitigation by a mild annealing procedure5 (baking effect), are not well understood. There is evidence the baking effect is related to a decrease of Nb2O3 and an increase of NbO2 from surface probes such as X-ray photoemission spectroscopy measurements applied before and after the baking6. However, the particular mechanism by which oxygen affects Q-slope is still elusive.

Here we report tunneling measurements on cavity-grade Nb that directly probe the surface superconductivity. Our results may provide new insights into the Q-slope problem and the baking effect. Air exposed, electropolished samples reveal a surface gap parameter characteristic of clean, bulk Nb (Δ=1.55 meV). However the tunneling density of states (DOS) is considerably broadened, exhibiting >30% zero-bias conductance. Samples treated using the same mild baking step that reduces the Q-slope (e.g., 120°C for 24h - 48h) show much sharper DOS and reduced zero-bias conductance. These results are interpreted as indicating that magnetic scattering of quasiparticles, likely from the Nb oxide layers, produces a gapless superconducting surface layer that contributes to RF dissipation.

A pristine Nb surface exposed to air develops a complex set of oxides including NbO, NbO2 and Nb2O5. Each of these oxides is thermodynamically stable with substantial off-stoichiometry. The topmost Nb2O5 layer is an ordinary band insulator with an energy gap >4 eV. Perhaps most significant is that sub-stoichiometric Nb2O5 (i.e. oxygen vacancies) develops magnetic moments7, a property that has been generally ignored in SRF cavity development. Below Nb2O5 is a more complex Peierls semiconductor8, NbO2, with a band gap ~0.1 eV. Next, NbO is a normal metal (Tc=1.3 K) that can lead to proximity effects with the adjacent Nb. Finally, the solubility of O in Nb is rather large (up to 22%), so dissolved O in the Nb region closest to the oxides can also produce a layer of reduced superconductivity (so-called poisoned
Prior to discussing the fits of the normalized data it is worth noting that there are numerous processes that could give rise to sub-gap conductance and therefore apparent gaplessness as measured by tunneling. These include proximity effects, severely degraded superconducting surfaces, and non-tunneling conductance processes (e.g. ohmic channels, hopping conductance, etc). However, a key feature of the data of Figs. 1 and 2 is a considerable peak shift toward higher voltages compared to the expectations of the Bardeen-Cooper-Schrieffer (BCS) DOS with $\Delta = 1.55$ meV: this narrows the range of likely explanations. This peak shift is seen more clearly in Fig. 3 where the baked sample conductance is compared directly to a BCS conductance at 1.7 K. The inset of Fig. 3 shows that the conductance peak of the unbaked sample is beyond 2.0 meV. None of the above processes that produce sub-gap quasiparticle states would produce a concomitant shifting of the peak to higher voltages.

If anything, proximity effects and degraded layers lead to reduced gaps and would shift the peak to lower voltages. Furthermore, additional conductance channels from inelastic or resonant tunneling would simply add to the overall measured conductance and not shift the peaks. The only mechanisms we are aware of that shift the conductance peak to higher voltages are pair-breaking phenomena such as those caused by strong-coupling effects (so-called Dynes lifetime effect) or scattering from magnetic impurities.

We stress that the fundamental process behind the Dynes effect should not be relevant at 1.7K<<$T_C$ and furthermore the data are poorly fit by this expression as shown in Fig. 3. Also, the Dynes effect gives a more rounded feature near zero bias than the V-shaped data.
would then prevent the adjacent Nb quasiparticles from acting as a protective non-magnetic oxide. This hypothesis might explain why the improved performances of baked cavities are neither affected by an HF rinse (removal of the NbO$_3$) nor by a thermal treatment in air or in vacuum.

In summary, tunneling measurements on SRF cavity grade Nb have provided new insights into the mechanism of the Q-slope problem and baking effect. The tunneling conductances reveal a gap parameter close to the optimal bulk value but with a broadened conductance for baked and unbaked Nb, indicating a pair-breaking process. This suggests that there is a contribution to RF dissipation arising from normal quasiparticle states inside the superconducting gap in a thin surface layer at the interface with the Nb oxide layers. A mild baking effect like that given to SRF cavities sharpens the conductance in the gap region and reduces the sub-gap quasiparticle density of states, thus remedying the dissipative effect. The only identifiable process for these effects is magnetic scattering, which is certainly plausible given the magnetic properties of reduced Nb oxides.

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