TUNNELING STUDIES OF MESOSCOPIC ALL-NBN JUNCTIONS

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Abstract—A scanning tunneling microscope (STM) was used to position a NbN tip near a NbN thin film sputtered on a Si substrate. Measurements at 4.2 K clearly show an energy gap of 5.0 mV. The Coulomb blockade of tunneling and the Coulomb staircase, formed by single-electron charging of the central electrode of a double capacitor system consisting of a substrate, a particle lodged in the oxide, and a tip, were observed at a number of points on the film. Experiments were repeated at room temperature. Fitting I–V and dI/dV–V curves to theory yields capacitances on the order of 5×10^{-19} to 2×10^{-18} F. The granular nature of the sputtered NbN greatly facilitates formation of the requisite double junction structure.

I. INTRODUCTION

In a tunnel junction of capacitance C and tunneling conductance G, the effects of a single tunneling event can be observed if the charging energy of the capacitor exceeds the thermal energy available to the electron ($e^2/2C > k_BT$), and if $1/G > R_Q = h/4e^2$ so that quantum fluctuations can be neglected [1]. Upon current- biasing the junction, no tunneling current is observed for voltages below $e/2C$. The difficulty with this scenario is that the (large) capacitance in the external leads completely swamps the low capacitance (on the order of 10^{-18} F = 1 aF) of the junction, thereby essentially voltage–biasing the junction so that no single electron effects can be observed. This problem has been circumvented by voltage-biasing two or more such junctions in series. A possible physical realization of this structure in the context of STM-formed junctions is shown in Figure 1. The large tunneling resistances of the junctions shield the capacitance of the common electrode environment from the stray capacitance of the leads. With this geometry the Coulomb blockade can be readily observed if the capacities and conductances are sufficiently low.

The Coulomb staircase is another effect which can be observed in tunneling characteristics of double junction structures. Incremental charging of the central electrode yields current plateaus in the I–V curves. Observation of the staircase is convincing proof that single-electron effects are really present, and not merely being imitated by some sort of oxide impurity effect [2].

In general it is somewhat difficult to construct these very small structures with sufficiently low capacities. Single-electron phenomena have been observed in ordinary tunnel junctions with particles embedded in the insulating layer [3, 4, 5], in ultra-small rigidly-fabricated junctions [6, 7], and in STM-formed point-contact-like junctions [8, 9, 10, 11, 12]. The first type suffers from a lack of control over the geometry of the tunneling path, and the second from technological limitations on the size which can be made, thereby necessitating very low temperatures. The third method (used here) has the advantage that extremely low capacitances can be achieved with sharp tips and close approaches to the substrate — the only reported room temperature observations [12, 13, 14] have used the STM. One disadvantage is that it is often difficult to locate a suitable double junction spot on a given substrate [8]. We have found, that although some searching is still required, sputtered NbN more readily lends itself to the formation of a double junction than any other material we have tried (Al-Al, W-Si, Nb-Nb, ...).

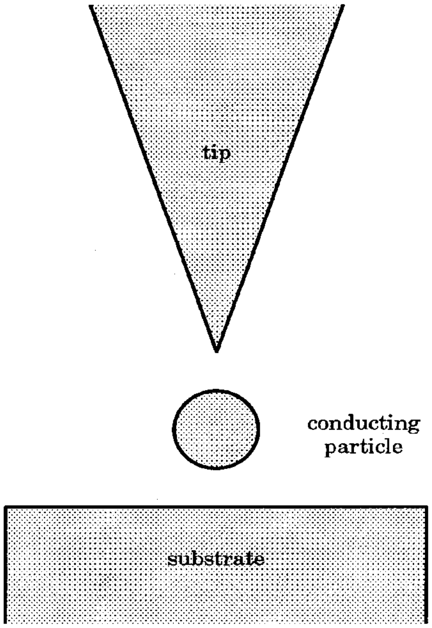

Figure 1: Schematic of a Physical Realization of the Double Junction System

II. EXPERIMENTAL DETAILS

To facilitate the formation of a double junction system, we predominantly used sputtered NbN tips and sub-

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strates. 6000 Å NbN films were reactively sputtered from a Nb target through an atmosphere of Ar, N_2, and CH_4 on to ultra-flat Si wafers at ambient temperatures. The superconducting transition temperature of these films ranges from 15–16 K. Tips were formed from 0.127 mm Nb wire cut at an angle at one end, and then chemically etched in a solution of HF and HNO_3 (10 : 1 by volume). Promising tips were selected with the aid of an optical microscope, and then deposited with NbN simultaneously with the substrates.

The system is cooled to 4.2 K. In the case of room temperature measurements a moderate vacuum is applied to stabilize the system and aid in noise reduction. The STM is used to position the tip, the feedback is disabled and the tip–substrate voltage ramped to the opposite polarity and back. Sweep rates ranged from 20 to 100 Hz. I–V curves are monitored on a digital storage oscilloscope, and conductance curves are then generated by numerical differentiation of the digitized waveform. Curves are often ported to a PC for further analysis. For some of the early He measurements a lock-in amplifier was used to measure the conductance directly after the I–V curve was measured. Agreement between the two methods was excellent, indicating that the curves were very stable.

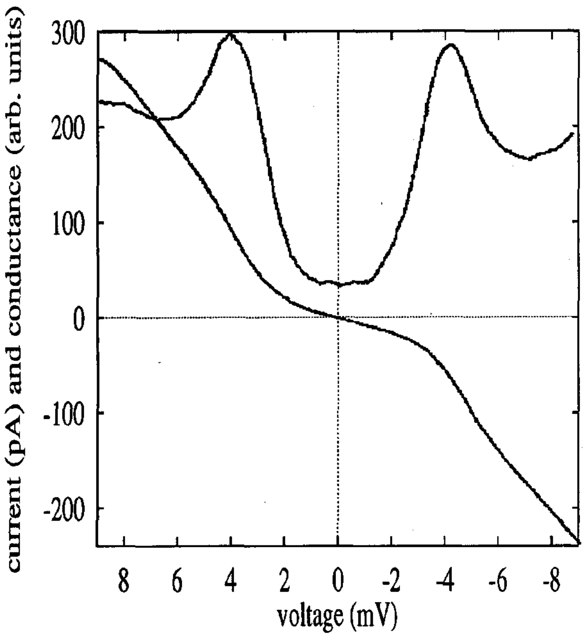

Figure 2: I–V curve taken below 4 K showing an energy gap of 5.0 mV for the NbN junction

III. RESULTS and DISCUSSION

The energy gap of NbN was clearly observed. A sample I–V curve is shown in Figure 2 yielding an energy gap of 5.0 mV. We have also been able to measure the energy gap of Nb (2.9 mV) in this manner using Nb tips and substrates; however in these Nb-Nb junctions, we were unable to locate a spot where either a Coulomb blockade or staircase could be readily observed. We attribute this to the relative difficulty of forming the double junction structure in Nb.

The double junction can be formed in several ways. There may be a conducting particle lodged in the surface oxide of the NbN. This is the situation depicted in Figure 1 and is probably the case most often encountered in experiment. Alternatively, the tip itself may acquire some NbN on its oxide layer after crashing into the substrate. Our experiments lead us to believe that both mechanisms occur with our system. For example, we tried a Nb tip with a NbN substrate. Before the tip impacted the substrate, only the familiar linear ohmic tunneling was observed. Following the crash, however, the blockade and staircase were observed; hence the Nb tip probably picked up some NbN thereby forming a double junction. This experiment confirms the notion that the granularity of the sputtered NbN does indeed tend to promote these multi-junction formations.

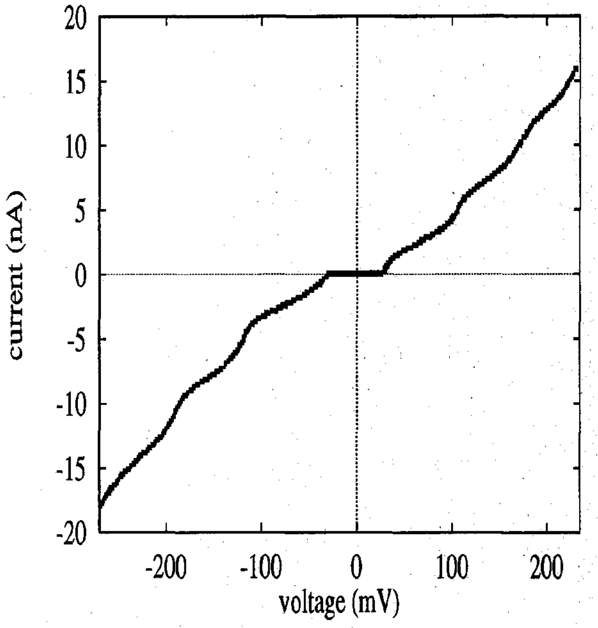

Figure 3: I–V curve at 4.2 K showing the Coulomb blockade and Coulomb staircase

An example of a Coulomb blockade and staircase measured with an all-NbN junction at 4.2 K is shown in Figure 3. The staircase is distinct and quite regular. From the periodicity in e/C, the larger of the two capacitances is found to be $C_2 = 2.5$ aF. Other parameters determined by a best fit to computer simulations are $C_1 = 2.0$ aF,

$R_1 = 2.8$ MΩ, and $R_2 = 14$ MΩ. Note also that the height of the first current step is half that of succeeding ones as the theory predicts [15].

Single-electron tunneling experiments have shown that it is possible for charge to be both discretely transferred across the barriers, and continuously transferred in junction electrodes. In particular, the central particle may carry non-integral background charge, or, in the case of the single-electron transistor, charge can be injected into this particle directly. A net non-integral charge, Q_0/e, on the particle naturally decreases the width of the horizontal section of the Coulomb blockade, and introduces an ohmic-looking linear part to the I–V curve. As Q_0/e increases towards 1/2, the horizontal Coulomb blockade is replaced by this linear component. Figure 4 shows a system where Q_0/e is nearly 1/2. Computer simulations fit this I-V curve with $Q_0/e = 0.49$, $C_1 = 4.25$ aF, $C_2 = 4.25$ aF, $R_1 = 1.0$ MΩ, and $R_2 = 2.5$ MΩ. This has also been observed by Hanna and Tinkham [10].

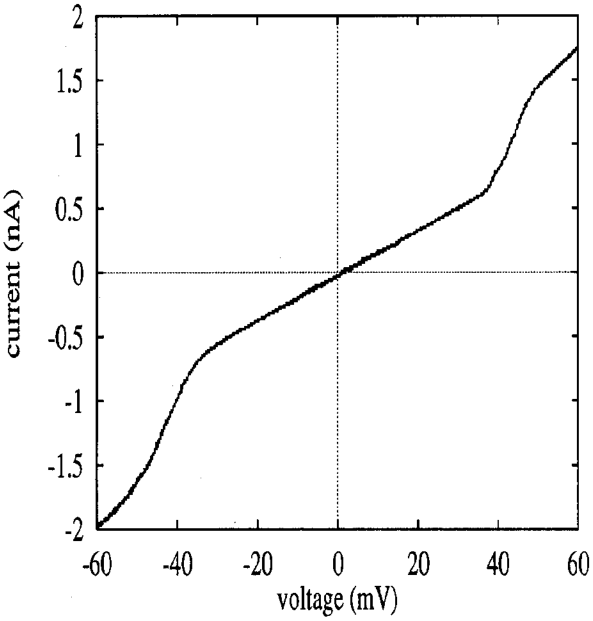

Figure 4: I–V curve at 4.2 K showing an initial charge offset of e/2 on the central electrode

As fits to other Helium-temperature measurements often yielded capacitances as low as 0.5 – 1.0 aF, we decided to repeat the experiments at room temperature. At 300 K, a capacitance of 1 aF corresponds to 3.1 k_BT so the effects should still be observable although the thermal rounding of the steps is much greater. The Coulomb blockade and staircase were indeed clearly observable, but with the expected thermal smearing. Room temperature presents other problems associated with the increased voltage noise, thermally-induced vibrations, and so on. In the case of Figure 5, the signal-to-noise ratio was improved by averaging over 32 sweeps, and the resulting cleaner signal was digitally filtered. A best fit to theory gives the parameters: $C_1 = .55$ aF, $C_2 = 1.2$ aF, $R_1 = 57$ MΩ, and $R_2 = 520$ MΩ with T = 300 K.

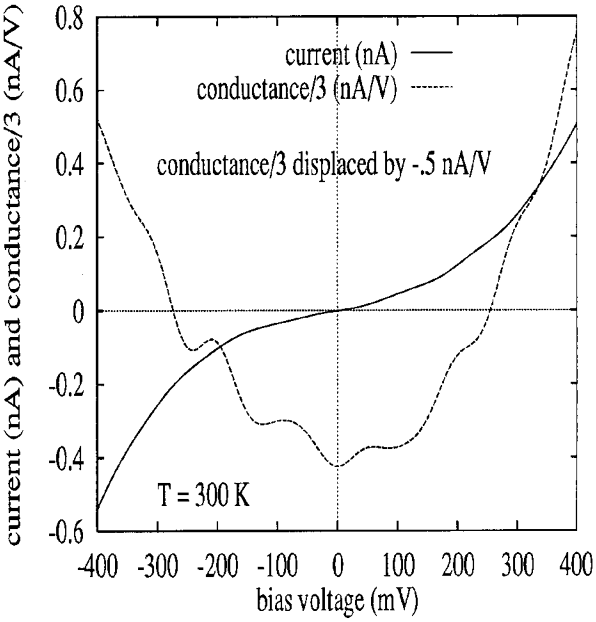

Figure 5: Room temperature observation of Coulomb blockade and Coulomb staircase

One feature reflected in Figure 5 not present in the given He temperature curves (but routinely seen in other curves nonetheless) is the increasing conductance. This can be attributed to a barrier effect or to changes in the density of states in the tip or particle. Wilkins et al. [5, 2] have modelled this behavior by adding a term proportional to V^3/R to the tunneling rates. Since the current is simply a weighted sum of the rates, the conductance assumes a parabolic character upon which the blockade and staircase are superimposed.

In an attempt to determine the size of the conducting grains forming the inner electrode of these systems, Atomic force micrographs (AFM) were taken of the NbN surface. Figure 6 is a schematic of one of these revealing a regular lattice of features of about 100 Å radius. The heights of these objects ascended up to 80 Å. Smaller features were unble to be resolved, but could very well exist.

The problems with estimating the particle size from capacitance data extracted from the I–V curves have been dealt with elsewhere [16, 8], dealing mainly with uncertainties in the exact junction geometry and dielectric. Nevertheless, assuming simple models for the geometry, and a tip-particle spacing of 10 Å, a capacitance of 1 aF corre-

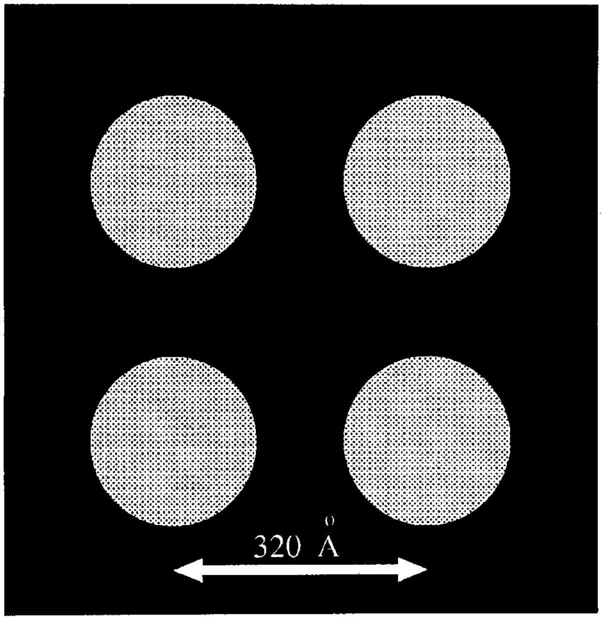

Figure 6: Schematic of AFM micrograph of a NbN substrate

sponds to a particle radius of between 30 and 50 Å. In view of the crudity of the assumptions, this is consistent with the AFM data, and at least give a physically realizable estimate.

In summary, tunneling studies were performed on STM-formed granular NbN-NbN-NbN junctions. Coulomb blockades and staircases were observed both at helium and room temperatures. I–V curves revealing fractional charge on the central particle were observed at helium. NbN seems to be a very promising material for the study of single-electron phenomena as it readily forms multi-junction structures with very low capacitance. Atomic-force microscopy reveals a lattice of particles of about 100 $\AA$ radius on the NbN surface, consistent with particle-size estimates from fitting the I–V curves to theory.

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