Squeezable tunneling junctions

by P. K. Hansma

Squeezable tunneling junctions establish the current state of the art for resistance stability of mechanically adjustable tunneling structures at $\Delta R/R \approx 0.1\%$. This is sufficient for use in connection with spectroscopies as subtle as phonon spectroscopy, but it is marginal and cannot at present be maintained to high enough bias voltage to permit molecular vibrational spectroscopy. Squeezable junctions have been used for characterizing bulk samples and for differential capacitance-voltage analyses of semiconductors.

1. Introduction

The success of Binnig, Rohrer, and co-workers [1] in obtaining atomic-resolution images has inspired a worldwide research effort in the field of tunneling microscopy. One of the most interesting questions is "How far can the stability be pushed?" This is an important question, since there are increasingly subtle levels of spectroscopy studies that could be carried out with the availability of increasing stability.

If stability in the tunneling resistance of the order of 50% could be obtained, tunneling microscopy and some electronic state spectroscopy studies could be carried out [1]. With stability of the order of 10%, superconducting energy gaps could be measured [2]. With stability of the order of 1%, some phonon spectroscopy studies should be possible. With stability of the order of 0.1%, most phonon spectroscopy and some molecular vibration spectroscopy should become possible. Finally, with stability of the order of 0.01%, it should become possible to obtain detailed molecular vibration spectra.

Through use of squeezable tunneling junctions [3], *x-y* translation is sacrificed, at least temporarily. However, their use permits exploration of the maximum stability in tunneling resistance that can be obtained in a mechanically adjustable tunneling structure.

2. Fabrication

Figure 1 shows a schematic view of a squeezable tunneling junction. Two flexible substrates are separated by evaporated thin-film spacers. A squeezing force adjusts the gap between the electrodes.

Figure 2 shows a photograph of one type of squeezable tunneling junction. The flexible substrates are two halves of one 2.5-cm × 7.5-cm glass microscope slide. The evaporated spacers and electrodes consist of thin films of Pb. The electrodes are narrowed where they cross to minimize dust particles in the junction area.

In fact, dust minimization is the one key to success, since the electrodes must be brought to within the order of 1 nm from each other. One dust particle of the order of 1 μm in diameter will clearly cause serious problems. Happily, the standard sort of dust minimization processes developed for the semiconductor industry—in particular, the use of submicron water filters for the water used in cleaning the substrates and the use of laminar flow benches for keeping substrates clean—are sufficient to minimize such problems when coupled to a good inspection system—for example, a binocular microscope with strong, nearly tangential illumination of the sample.

3. Experimental results

Figure 3 demonstrates that squeezable tunneling junctions can be operated with various materials in the gap. The liquid (oil) was introduced by capillary action on a drop placed near the edge of a completed junction. The solid,

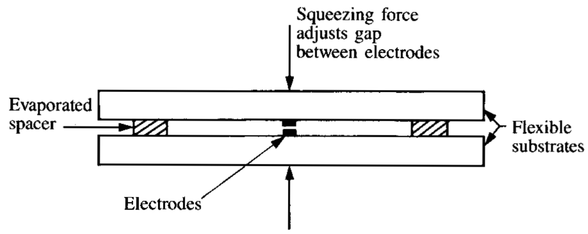

Figure 1

Schematic view of a squeezable tunneling junction.

naphthalene, was introduced while the junction was heated with heat lamps above the melting point of naphthalene. The junction was then adjusted with a squeezing force and the naphthalene was allowed to solidify. These data were obtained by squeezing with an electromagnetic squeezer that has been described elsewhere [4].

Figure 4 demonstrates that squeezable tunneling junctions can be operated with negligible leakage current. Leakage current, due for example to microshorts, shows up as current below the superconducting energy gap. Note that this current is negligible for this junction, showing that essentially all of the current flow is due to electron tunneling. Figure 4 also demonstrates the second plateau of stability mentioned in the introduction. In order to measure the superconducting energy gaps, Δ_{Pb} and Δ_{Al}, a resistance stability of the order of 10% is required. (The stability in this figure is higher than that.)

Figure 5 demonstrates achievement of the fourth plateau of stability, at least at low bias voltages. The peaks labeled TA and LA are the transverse acoustic and longitudinal acoustic phonon peaks of the aluminum electrode. Observation of these relatively weak phonons requires a resistance stability of the order of 0.1%. Unfortunately this stability is not maintained beyond 40 mV, where molecular vibrations would be observed [5]. Peaks from molecular vibrations are of the same order of magnitude as the aluminum phonons [5]. They cannot, however, be seen in this curve because of a dramatic increase in noise beyond 40 mV.

The reason for this noise is not understood at present. Possibilities include 1) switching between different current paths in the junction, 2) motion of mobile species (possibly atoms) into and out of regions of high current density, and 3) coupling between electromagnetic forces in the junction and the mechanical structure.

Further investigation with electrodes differing in roughness, different absorbed species, and different mechanical structures should shed light on this present limit on the stability of mechanically adjustable tunneling structures.

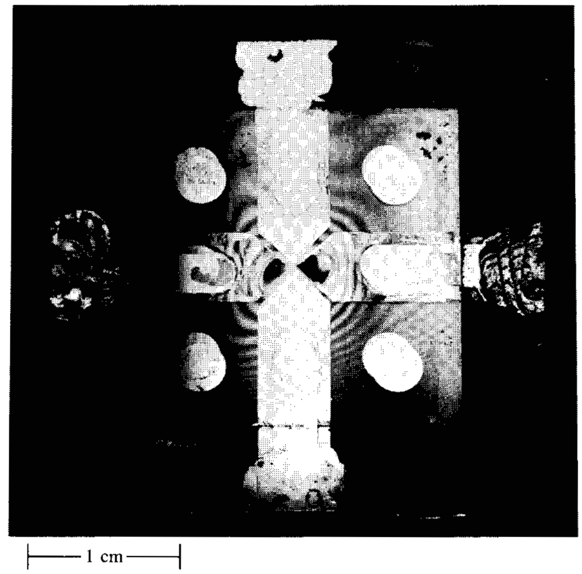

Figure 2

Photograph of a squeezable tunneling junction after cycling to 4.2 K and squeezing.

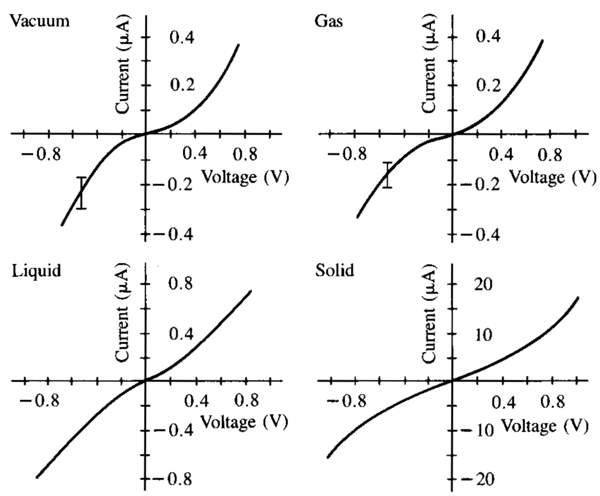

Figure 3

Current vs. voltage curves for squeezable tunneling junctions operated with vacuum, gas (air), liquid (oil), and solid (naphthalene) in the gap.

4. Applications

Figure 6 demonstrates the extension of the squeezable tunneling junction method to include the possibility of tunneling to bulk samples—in this case [6] from

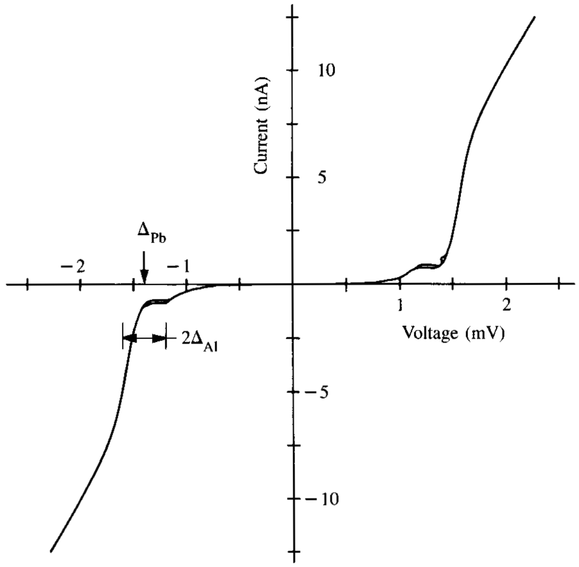

Figure 4

Current vs. voltage curves for a squeezable Al-barrier-Pb tunneling junction at 1.2 K, submerged in liquid helium.

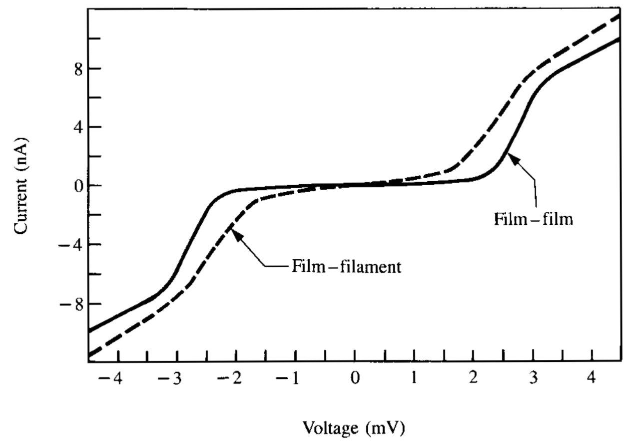

Figure 6

Current vs. voltage curves for Nb film–Nb film and Nb film–Nb filament squeezable tunneling junction at 4 K, submerged in liquid helium.

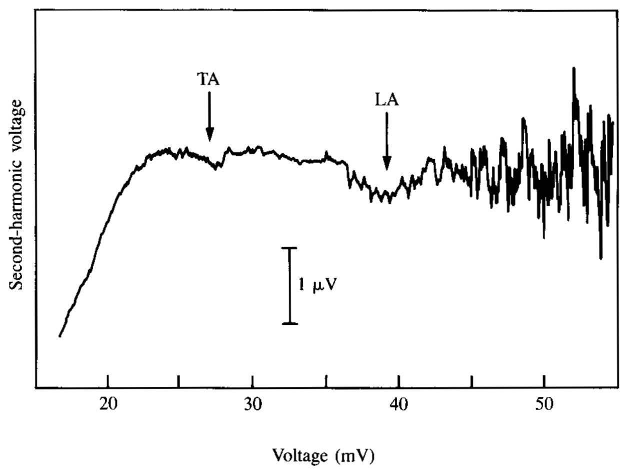

Figure 5

Second-derivative curves for an Al-barrier-Pb squeezable tunneling junction at 1.2 K, submerged in liquid helium.

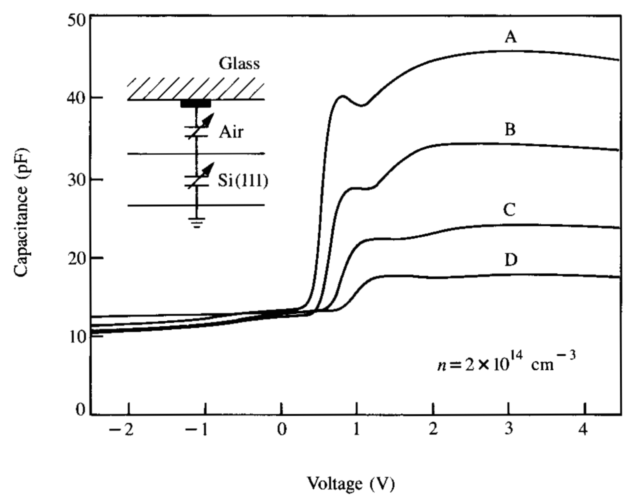

Figure 7

Differential capacitance vs. voltage curves for a squeezable junction formed by using a Si(111) wafer as the lower electrode. Use was made of a larger electrode (1 mm diameter) than in previous figures. The estimated air-gap thicknesses for Curves A-D are 1700, 2200, 2900, and 3600 Å, respectively.

superconducting Nb films to filaments of superconducting Nb wire. That work is currently being extended to profiling of the superconducting energy gap through wire by successive etching and tunneling [7].

Squeezable tunneling junctions have also been made to bulk semiconductor samples including silicon and mercury-cadmium telluride [8].

Figure 7 demonstrates the extension of the squeezable tunneling junction method to the differential capacitance-voltage analysis of semiconductors [9]. The variable air capacitor is adjusted by changing the spacing between the electrode and semiconductor surface by squeezing. In the figure, results are shown for n-type Si(111). The capacitance change is due to the change in surface charge depletion caused by the electric field as the voltage between the electrode and the silicon is changed. This changing capacitance versus voltage can be used to help determine surface properties, such as the ionized donor density. Use of the squeezable tunneling junction approach offers the possibility of following associated surface properties through a sequence of processing steps without modifying the surface (which occurs as a result of the usual need to form oxide-barrier capacitors in order to carry out such differential capacitance-voltage studies).

5. Concluding remarks

Squeezable tunneling junctions can be set to different resistances by changing a mechanical squeezing force from an electromagnet. Typical values of resistance are 10 kΩ to 10 MΩ for a 50-μm × 50-μm junction. Resistance stability of the order of 0.1% can be obtained without vibration isolation. There is an inherent immunity to vibration that comes from immersing the junctions in fluids: For the two substrates to approach or separate, fluid must flow into or out of the junction. The time constant for this flow is of the order of one second.

Future research opportunities include 1) understanding the current stability limits, 2) extending those limits and thus making molecular vibration spectroscopy possible, and 3) applying the basic principles to a variety of technological problems including semiconductor characterization. With regard to the latter, a new type of mechanically adjustable tunneling junction, the "break" junction [10], is promising for studies of freshly exposed surfaces of fractured samples.

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