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EXPERIMENT ON THE DYNAMICS OF TUNNELING THROUGH METAL OXIDE BARRIERS

H. Hübner

Institut für Angewandte Physik, Universität Tübingen, Auf Der Morgenstelle 12, D-7400 Tübingen, F.R.G.

Résumé - Une pointe d'émission de champ en tungstène a été utilisée dans un résonateur supraconducteur à 12...18 GHz. Les observations indiquent que le courant émis par des pointes oxydées est finement contrôlé par la forme et aussi la charge de la barrière de potentiel de l'oxyde.

Abstract - A tungsten field emitter has been operated in a superconducting resonator at 12...18 GHz. The observations indicate that the emission current of oxidized tips is sensitively controlled by the shape and thus by the charging of the oxide barrier.

Introduction

The shape of potential barriers, formed by adsorbates or oxides is very sensitive to charging of the dielectric layer and the tunnel current through these barriers is a sensitive instrument to detect integrally changes of the barrier shape. There are many possibilities for the location of charges within a semiconducting or insulating layer, but each of them has a different time constant. Surface states on semiconductors with time constants of seconds already had been measured in the 50th /1/. Faster states are to be expected within the adsorbate or even faster at the metal - adsorbate interface with time constants beyond the microwave frequencies. Thus the comparison of field emission currents at different frequencies seems to be able to separate the contributions of the various charging mechanisms.

Experimental Arrangement

To learn what difficulties are to be expected, we built up a preceding experiment /2/: A tungsten field emitter is operated in a superconducting resonator at 12..18 GHz (cf. Fig.1). The tip is mounted on the axis where a strong E-field concentration occurs with a parallel plate capacitor field configuration. Everytime the needle becomes negative with respect to the opposite wall, an electron bunch will be emitted. The integral emission current as a function of the field strength is recorded.

In order to get FN-plots one must plot \( \lg\left(\frac{I}{E_0^{3/2}}\right) \) vs \( 1/E_0 \) instead of \( \lg(I/E^2) \) vs \( 1/E \) (\( E_0 \) = amplitude of the electric field), due to the shape of the electron bunches.
A cleaning of the tip in this arrangement only can be achieved by heating it with the aid of displacement currents in the strong high frequency field of the resonator.

**Fig. 1:**
1 - resonator  
2 - wave guide  
3 - collector  
4 - pumping tube  
5 - measuring chamber  
6 - feed through

**Results**

The freshly cleaned tips show smooth FN-plots, which are in agreement with the dc results. Expect very low work functions (around 2 eV), which are not understood as yet and call for some further investigations.

**Fig. 2**

\[ \log(I/E^{3/2}) \]

\[ 1/E_0 \]

**Fig. 3**

\[ \Delta \log(\text{...}) \]

\[ 1/E_0 \]
Contaminated tips show FN-plots with a characteristic wavy structure (cf. Fig.2 and Fig.3). Common to these waves are increasing wave lengths and amplitudes towards lower currents and about two or three oscillations per FN-plot. The work functions as a function of the degree of contamination show a saturation behavior and lie around 3 eV.

In the following we will attempt to explain the low work functions and the wavy FN-plots, assuming an oxide layer to be present. The argumentation will be close to the interpretation in case of field emission in MOS-structures, where one gets FN-plots with exactly the same kind of modulation /3/.

Discussion

The most stable oxide of tungsten is $\text{WO}_3$. It is a semiconductor with a gap of $2.5 \ldots 3.5$ eV, a dielectric constant of 20 and a work function of 6.2 eV. It grows by a CABRERA MOTT process to a thickness of about 2 nm. If one constructs a barrier with these values (Fig.4a) it seems to be unlikely that such a barrier will emit electrons. But this picture is too simple: Tungsten forms a lot of mixed oxides $\text{W}_x\text{O}_y$ rather than a well defined oxide layer. Thus excess metal atoms form a n-type surface layer between the tungsten bulk and the oxide (Fig.4b). These donor states can be discharged into the metal and thus bias the barrier by some volts. This leads to the small work functions $\varnothing'$ despite of the initially high value of more than 6 eV at the oxide - vacuum interface.

Now a second effect becomes important. The bias pulls the conduction band below the Fermi level. So the electrons in the first step tunnel into the cb, propagate there nearly free and tunnel later through the FN-barrier into the vacuum. Provided the mean free path in the cb is long enough to avoid scattering, there will develop a resonant electron wave function. The tunnel current now is no longer controlled by the FN-barrier alone, but it is modulated by a resonant term, depending on what kind of resonance can grow in the cb of the oxide. This condition is very sensitively controlled by the applied electric field.
Of course, this charging has nothing to do with the presence of an rf field. It is a purely static effect, characteristic for the metal - metal oxide - interface being apparent at microwave frequencies too.

Finally this first experiment had two important results:

1) It is possible to operate a field emitter (and to apply the FN-Eq.) with any restrictions even at microwave frequencies. This result is of interest for electron optical applications too.

2) The differences between dc and rf field emission are not weighty - nevertheless they promise to be very informative - and call for a highly sensitive experimental set up.

Fig.5: 1 - liquid nitrogen  
2 - liquid helium  
3 - wave guide  
4 - anode  
5 - view port  
6 - screen  
7 - channeltron FN-plot  
8 - channeltron energy

Improvements

Encouraged by the first results, we constructed a new experiment, which is outlined in Fig.5. Now the resonator not longer is submersed in LHe. This allows a more flexible construction. E. g. it will be possible to shift axially the needle. Outside the resonator the tip can be investigated by dc field emission. When it is pulled back into the resonator the same measurement can be made at three frequencies between 12 and 18 GHz. Both times the emission patterns can be imaged on a screen. Below the screen an energy analyser and two channeltrons are mounted allowing the measurement of the emission currents from 0.1 electron per second up to 1 mA - 17 decades without a gap. This assembly can be shifted with respect to the tip. Thus FN-plots and the energy distribution of the emission current of selected crystal faces can be measured in clean and contaminated state. In a subsequent state of the experiment time resolved measurements are planned.
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