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Experimental Evidence of Hot Electron Detection with Scanning Hot Electron Microscopy (SHEM)

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Scanning hot electron microscopy (SHEM) is an experimental technique conceived to obtain the spatial distribution of hot electrons in a device. In this communication we present the first experimental results confirming SHEM operation. Hot electrons with energies of 3 eV are injected by means of a $Si/CaF_2/Au$ heterostructure and subsequently detected at the tip of a scanning tunneling microscope in the SHEM configuration. The measured hot electron current is 4 pA for a tunnel current of 5 nA.

The necessity of an experimental technique for a complete characterization of the properties of hot electrons in a device is evident, since ballistic transport of hot electrons in metals and semiconductors is expected to result in faster and more efficient devices. We have proposed[1)] scanning hot electron microscopy (SHEM) as a technique derived from conventional scanning tunneling microscopy (STM), with the potential for direct observation of the spatial and energetic distributions of hot electrons. The possibility of hot electron detection with SHEM has been previously reported[1)] from a theoretical analysis of the conditions necessary for SHEM operation. Here we present the first experimental evidence of the validity of the method.

Before entering in the explanation of the experimental results, it seems convenient to mention here the most prominent features of SHEM, which are:

1) The gap barrier between the STM tip and the sample surface is lower than the hot electron energy, so that hot electrons reach the tip by surmounting the barrier instead of tunneling through it. Otherwise the hot electron current becomes much smaller than the current of electrons in thermal equilibrium that appears as a consequence of the residual resistance present at the sample surface.

2) Hot electrons (Fig. 1) should be emitted with a minimum energy in order to be detected. The value of this energy depends on the materials chosen for the sample surface and the STM tip, and typically vary from 0.5 eV to several eV. As previously reported[2)], the Si/CaF_2 heterostructure can be used as a universal hot electron emitter for SHEM, since it can communicate accelerating energies as high as 5 eV.

The results we present here correspond to hot electrons emitted by a $Si/CaF_2/Au$ heterostructure and flowing toward a Pt-Ir tip. The structure of the sample prepared is shown schematically in Fig. 2(a). The CaF_2 region consists of a single crystal grown[3)] by MBE at 650℃ with a background pressure of 2×10^{-8} Torr, and its thickness is 8 nm, or 26 monolayers. In order to minimize the series resistance present at the sample surface, the emitter is limited to a small area of approximately 10 mm^2, and the gold layer is made thicker everywhere else. Gold has to be deposited all around the emitter, since otherwise the STM tip would crash on the sample surface when searching for the emitter. Current densities obtained with this sample are on the order of several KA/cm^2, as seen in Fig. 2(b). According to our theoretical results for this material combination[1)], hot electrons must have energies of 3 eV or higher in order to be detected by SHEM; for an applied voltage of 3 V, the current generated by the emitter is 0.37 mA, resulting in a current density of 37 KA/cm^2.

Experiments were carried out in air with a dc sample bias $V_S = 3$ V coupled with an ac voltage 0.17 Vp-p in amplitude and a frequency of 82.8 Hz. This ac component is used for harmonic detection by means of a lock-in amplifier. The tunnel voltage was kept constant at $V_T = 1.5$ V, The hot electron current is measured as a function of the tunnel current, and the final results are shown in Fig. 3. For low tunnel currents (corresponding to wide gaps between tip and sample), hot electrons cannot surmount the gap barrier and the detected current is zero. When the tunnel current is increased, the gap distance becomes shorter and this causes a lowering of the gap barrier until hot electrons can surmount it, resulting in a sudden increase of the measured output. As seen in the figure, the detected hot electron current is approximately 4 pA for a tunnel current of 5 nA.

If $J_{EM} = 37$ KA/cm^2 is the current density generated at the emitter, h_{hot} is the transmission efficiency of hot electrons from the emitter to the STM tip, and A_{hot} is the effective surface of the tip for hot electrons, we can write the hot electron current as

$$I_{hot} = J_{EM} \times \eta_{hot} \times A_{hot} = 3.7 \times 10^4 \ \mathrm{A}/\mathrm{cm}^2 \times 10^{-3} \times 10^{-13} \ \mathrm{cm}^2 = 3.7 \ \mathrm{pA} \qquad (1)$$

Therefore, the results obtained are consistent with the results expected theoretically for a hot electron transmission efficiency of 1/1000 and an effective surface of the tip of 10 nm^2.

Figure 2 shows also a theoretical simulation of the results, that was adjusted to the experimental data by means of a fitting parameter. In this simulation, the hot electron current is calculated as

$$I_{hot}(V_S, V_T, d) = K(V_S) \times \int_0^\infty f(E, V_S) P_g(E, V_T, d) dE \qquad (2)$$

where K is a parameter determined by the emitter current density and the effective surface of the STM tip, and $Pg(E, V_T, d)$ is the transmission efficiency across the gap expressed as a function of the hot electron energy, tunnel voltage and gap distance. The distribution function $f(E, V_S)$ is introduced to simulate the partial relaxation of hot electrons in the metallic base, and is strongly modulated by a relaxation parameter E_{relax}[4]; the best fitting in Fig. 3 was obtained for $E_{relax} = 50$ meV.

In summary, we have presented the first experimental demonstration of SHEM operation. Although these are only preliminary results, they show the potential of the technique as a suitable tool for the study of electron wave phenomena in semiconductor structures.

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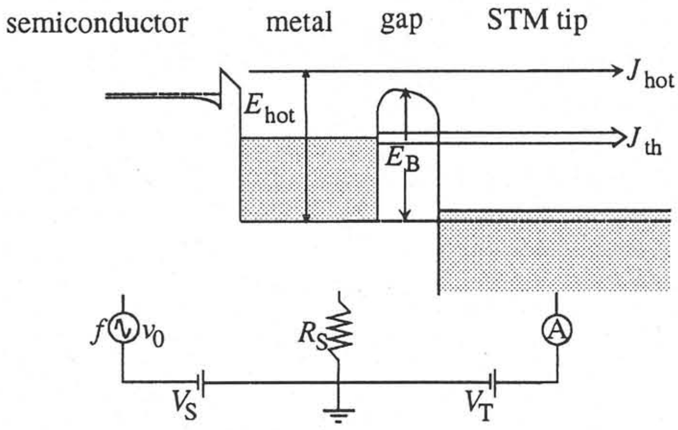

Figure 1:Operational principles of scanning hot electron microscopy (SHEM). The hot electron current J_{hot} flows against a background current of electrons in thermal equilibrium J_{th}.

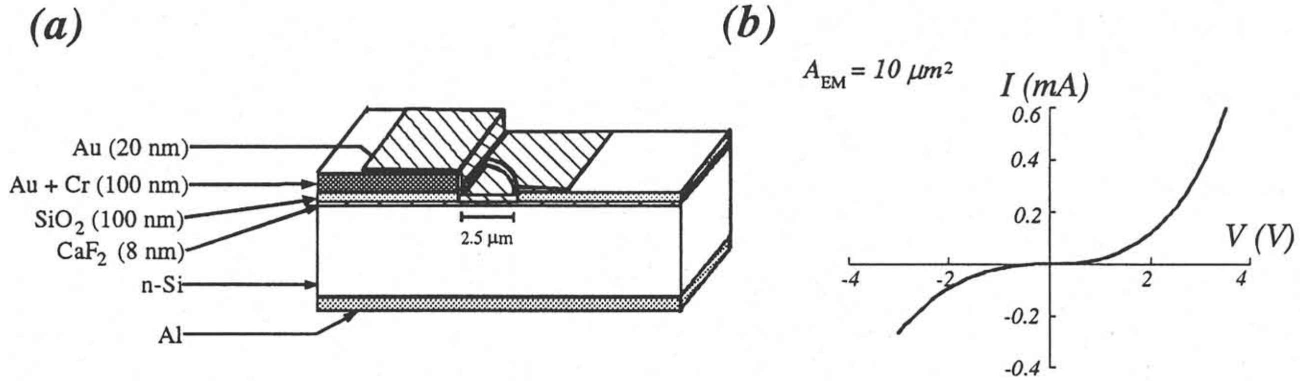

Figure 2: (a) Section (across the middle of the emitter) of the sample prepared for hot electron detection with SHEM. The emitter has an approximate area of 10 mm^2. (b) Experimental I-V characteristics of the sample. The current density generated at the emitter is 37 KA/cm^2 for an applied voltage V_S = 3 V.

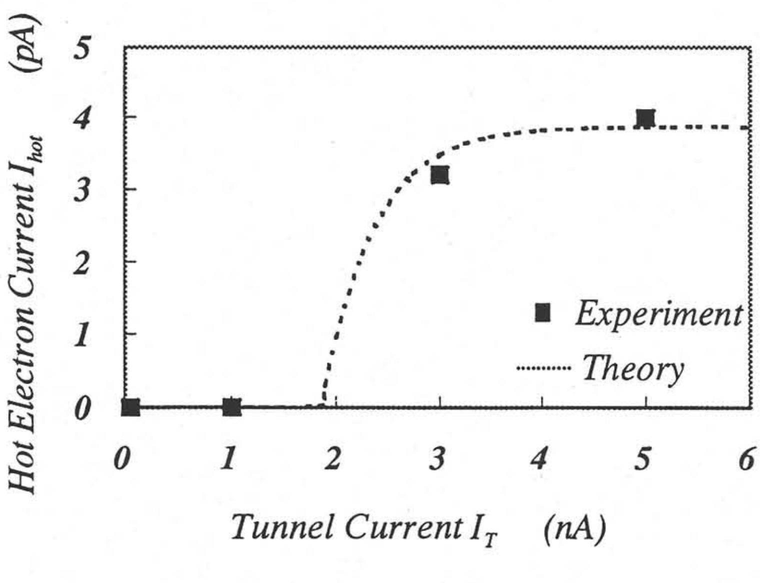

Figure 3: Final experimental results, proving that detection of the hot electron current has been achieved with SHEM. The detected hot electron current was approximately 4 pA for a tunnel current I_T = 5 nA. These results are in good agreement with those expected theoretically for η_{hot}= 10^{-3} and A_{eff} = 10 nm^2.