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Measurements of Modulation of the Current in a Field Emitter caused by a Laser

M. Brugat and M.J. Hagmann

Department of Electrical and Computer Engineering, Florida International University, Miami, FL 33199, U.S.A.

Abstract. Numerical simulations suggest that laser illumination of a field emitter increases the tunneling current due to a resonant interaction in which tunneling electrons exchange quanta with the laser. Thus, a laser may be used as a gate, and a time-varying current is produced if the laser is amplitude modulated. We have measured an RF tunneling current of 0.4 nA when the tungsten tip of a sealed field emitter tube is illuminated with a laser diode that is amplitude modulated at 1 MHz, and the DC current is 5 μ A. The laser diode increases the DC current by 270 nA, which is attributed to tip heating. However, the RF current (0.4 nA) has a period less than estimates of the thermal relaxation time.

1. INTRODUCTION

Previous numerical simulations suggest [1] that laser illumination of a field emitter increases the probability of tunneling due to a resonant interaction in which tunneling electrons exchange quanta with the laser. Further simulations suggest [2] that if the laser is amplitude modulated then the tunneling current will have a RF component at the modulation frequency. That is, the laser acts as a gate when the modulation frequency is much less than the optical frequency, so that the peak to peak value of the RF current is equal to the magnitude of the change in current if the laser were operated in CW mode. We have made preliminary experiments in order to test some of the results of these simulations.

2. SUMMARY OF RELEVANT SIMULATIONS

Numerical methods described previously [3] are used to solve the time-dependent Schrödinger equation in order to determine the steady-state response of tunneling electrons to a laser. However, the previous simulations were limited to particles having a single energy, and now density functional theory [4] is used to determine the self-consistent static potential for a given applied static field and a set of energies representing the distribution in a one-dimensional jellium model of a tungsten tip. The present simulations are not completely self-consistent because the static potential is not corrected to allow for changes in the charge distribution caused by the radiation field. However, a partial correction for this effect is made by adjusting the incident electric field to allow for screening by the metal [5].

Simulations were made in order to optimize the experimental conditions so that the change in current caused by a laser diode operating at 690 nm would be measurable. The effects of the tip size were determined by making the approximation that the total current is found by multiplying the current density for the one-dimensional numerical model by the surface area of a hemisphere having the specified value of tip radius. Iterations were performed to determine the value of the applied static field that is required to obtain a nominal emitted current of 23 nA with tungsten tips of various sizes at 200°C when there is no laser. The results of

these iterations, graphed in Fig. 1, show that the required value of the applied potential increases linearly with the tip radius. Increasing the tip radius increases the emitting area but also decreases the current density, and the net effect of these two changes is that a larger applied potential is required to maintain the same value of emitted current as the tip size is increased. Figure 2 shows the change in the emitted current (from the nominal value of 23 nA) caused by a CW laser with a power flux density of 10^{10} W/m², as a function of the optical wavelength. The six separate curves are for different tip radii from 175 to 50 nm (from top to base of the figure). The value of the applied static field used in the calculations for each tip radius is that in Fig. 1.

Figure 1: Applied static field and applied potential required for a current of 23 nA, as a function of tip size for tungsten at 200°C when there is no laser.

Figure 2: Change in emitted current due to a laser as a function of optical wavelength for a tungsten surface at 200°C with tip radii of 175, 150, 125, 100, 75 and 50 nm (top to base) and a power flux density of 10^{10} W/m².

The results shown in Fig. 2 suggest that a relatively large tip size should be used in the experiments in order for the laser to produce a larger change in the emitted current. This effect may be understood in that a smaller value of the applied static field is required to obtain the same current when the tip size is increased, and thus the relative effect of the optical electric field on the barrier height is increased. The optically-caused modulation in the emitted current occurs when the optical electric vector is oriented normal to the tip in order to superimpose with the static field so that the height of the barrier is varied by the laser.

Figure 3 shows the change in the emitted current (from the nominal value of 23 nA) caused by a CW laser as a function of the optical wavelength, for a tungsten tip at 200°C with a tip radius of 175 nm. The four curves are for power flux densities of 10^{11} , 10^{10} , 10^9 and 10^8 W/m² (from top to base of the figure). The value of the applied static field used in the calculations is 4.58 V/nm, as shown in Fig. 1 for the chosen tip radius of 175 nm. These simulations show that the increase in emitted current is directly proportional to the power flux density of the laser, which may be understood in that the resonant interaction is caused by the exchange of quanta between the tunneling electrons and the laser.

Figure 3: Change in emitted current due to a laser as a function of optical wavelength for a tungsten surface at 200°C with tip radius of 175 nm, and power flux densities of 10^{11} , 10^{10} , 10^9 and 10^8 W/m² (top to base).

3. DESCRIPTION OF THE APPARATUS

Figure 4 is a block diagram of the apparatus. We used a sealed field emitter tube (Leybold AG model 55460) having a bulb radius of 5 cm, a maximum current of 10 μ A, and a monocrystalline tungsten tip that was prepared by etching. The tip has a nominal radius of 100-200 nm, but the magnification ratio suggests a value closer to 200 nm which is consistent with the requirement for a relatively large size as suggested by our simulations. While the level of the vacuum in this tube does not guarantee a clean tungsten surface, the tip was cleaned by passing a current of 1.95 A through the filament for a period of 1 minute immediately before each measurement as suggested by the manufacturer. The characteristic pattern for tungsten was clearly visible on the phosphor screen during each measurement.

Figure 4: Block diagram of the apparatus

The field emitter tube is mounted in a cylindrical copper shield and all connections are shielded to minimize the effects of interference. A Fluke model 410B high voltage power supply with a $200\text{ M}\Omega$ ballast resistor supplies a potential of approximately 9,000 V, which is adjusted for an emitter current of $5\text{ }\mu\text{A}$ DC with no laser. The tip electrode of the tube is connected to a custom-made FET preamplifier by a $0.01\text{ }\mu\text{F}$ blocking capacitor, and also to ground by a $1\text{ M}\Omega$ resistor in order to provide a dc path. The preamplifier, which is based on a CF739 FET and a MARS-6 MMIC (monolithic microwave integrated circuit), has an input impedance of $100\text{ k}\Omega$ and a voltage gain of 10 at the frequency of 1 MHz which was used in the measurements. The output of the preamplifier is fed to a Tektronix 2230 digital storage oscilloscope.

The optical source used in these experiments is an index-guided laser diode (Toshiba TOLD9150) having a power of 30 mW and a center wavelength of 690 nm. Both astigmatic and anamorphic correction are used in focusing the diverging elliptical beam to a minimum spot size at the tip, where the power flux density is approximately 10^8 W/m^2 (spot radius $\rho \approx 6\text{ }\mu\text{m}$). A three-axis ball slide translator is used to position the laser diode, and the laser diode is also rotated on its axis so that it is polarized with the electric vector oriented normal to the tip surface (parallel to the shank). The laser diode is biased into operation with the DC supply, and modulated at a frequency of 1 MHz with a 5 V peak square wave from a Tektronix FG504 function generator.

4. EXPERIMENTAL RESULTS AND CONCLUSIONS

The magnitude of the RF tunneling current is determined by taking the difference between traces recorded on the oscilloscope when the laser diode is on and when it is off. We also compare these data with the values for consecutively measured controls in which the laser diode is operating but the light is interrupted by an opaque screen. The oscilloscope is operated in the signal averaging mode with $N = 5000$ to reduce the effects

of noise.

When the focusing is adjusted for minimum spot size at the tip and the polarization is adjusted so that the electric vector is parallel to the shank we find that the DC current is maximum. Under these conditions the DC current is increased by approximately 270 nA from the standard value of 5 μ A without the laser, a change which is attributed to tip heating. Under these conditions we measure an RF tunneling current of approximately 0.4 nA peak at the modulation frequency of 1 MHz. In every set of measurements, we found that adjusting the focusing and polarization in order to maximize the DC current also resulted in a maximum value for the RF tunneling current.

It should be considered that the observed RF tunneling current may be caused by tip heating. In that case, the magnitude of the RF current measured at 1 MHz would be consistent with the observed thermally-caused increase in the DC current if $0.8/270 = \exp(-0.5 \mu\text{s}/\tau)$. But this requires that the thermal relaxation time would have to be approximately 86 ns. Simulations of laser-caused tip heating [6] show that the thermal relaxation time is strongly dependent on the shank length and the size of the focal spot, but values two orders of magnitude greater than 86 ns are typical with the spot size ($\rho \approx 6 \mu\text{m}$) used in these experiments. Thus, we believe that the observed RF tunneling current is not due to tip heating. We have noted that the RF tunneling current is maximum when the focusing and polarization are adjusted to maximize the increase in the DC current caused by the laser. However, our simulations of the resonant interaction show that it has several characteristics in common with thermal effects in that 1) both are maximum when the optical electric vector is oriented normal to the tip, 2) both are maximum when the power flux density is increased by focusing for a minimum spot size, and 3) the RF current caused by the resonant interaction, and the increase in the DC current caused by heating, both increase in direct proportion to the optical power of the laser. Further studies using lasers at several optical wavelengths, modulation over a wide range of frequencies, and precise control and measurement of the spot size are needed in order to fully test the theory.

It appears that the measurement of RF tunneling currents when the laser is amplitude modulated would be a useful tool for separating thermal from non-thermal effects when studying photofield emission. Photofield emission [7] offers promise as a means for measuring the band structure of metals. However, Lee and Robins [8] showed by measurements and simulations that thermal effects are present in the experimental data for photofield emission. Mechanical choppers have been used to decrease the effects of tip heating in photofield studies, and it is claimed [9] that the thermal component of the photocurrent is reduced by 40 percent by chopping at a frequency of 8.5 kHz. It is reasonable to expect that thermal and non-thermal effects could be completely separated by using RF measurements at a high enough frequency.

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