Laser Induced Annealing Dynamics of Photo-Electron Spectra from Silicon Field Emitter Arrays

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Abstract: A marked increase in electron yield, an overall spectral red shift, and the formation of a higher energy peak from Si field emitter arrays (FEAs) are observed in photo-electron spectra throughout a laser annealing process.

1. Introduction

There has been a recent surge of interest in laser induced electron emission from solid surfaces[1–4] due to their many potential applications, including free-electron laser sources and attosecond time-resolved microscopy. However, in order to achieve efficient electron yield at a low emittance without damage from laser sources, some means of local field enhancement is required. In general, this necessitates the use of plasmon resonance, localized nano-structuring, or both. From the perspective of generating high flux, low emittance, monoenergetic beams, sharp localized regions of field-emission seem favorable to planar film emission from plasmon fields [4], thus providing further motivation for using an array of tips as a preferred electron source.

In order to achieve higher flux per bunch (compare to [2]) we are using a 10 μm pitch array of silicon emitters each having between 5-10 nm radius of curvature at the tip apex, and a higher power laser at 1 kHz. Silicon combines the advantage of having well established fabrication techniques together with less stringent vacuum requirements. Bypassing the need for in-situ annealing and preparation of the tips, we present here a spectrally resolved study of the annealing dynamics of such a structure using the laser drive source to anneal the tips. Initial measurements show a qualitative agreement with theory concerning field-emission in the presence of thin oxide layers[5].

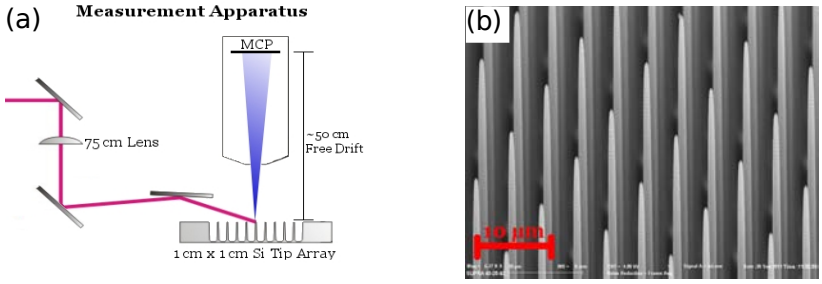

Fig. 1 – (a) Schematic of the measurement apparatus used. Electrons propagate through a 50 cm field free drift tube before striking an MCP. (b) SEM of the tip structures used.

2. Experiment Setup

Our experimental setup is shown in Fig. 1. A Ti:sapphire amplifier provides 35-fs-pulses which are focused to spot of 160 um diameter using a CaF2 lens (focal length: 75 cm). This leads to a peak field of ~1.05×10^9 V/m in the bare focus. The focused beam illuminates the entire 1cm wide tip array along the direction of propagation at a grazing incidence. Emitted electrons then travel through a time of flight (TOF) spectrometer. The the spectra are measured directly without the need of post processing, allowing superior SNR per shot.

The incident pulse energy was scanned over a range fom .2-.6 uJ with a step size of .1 uJ. Between each sequence of spectral measurements, an annealing step was performed using incident energies ranging from 1.5-2 uJ at time spans ranging from 5-15 minutes.

3. Results

The experimental results are compiled in Fig. 2. When observing the spectra, one notes a red shift after each

annealing step. An electron with initially zero velocity inside of a strong laser field has an average energy of one ponderomotive potential, $U_p = e^2F^2/(4m\omega^2)$, and a classical energy cutoff of $2U_p$, where F is the peak field stregnth, m the mass of an electron, ω the center frequency and e the charge of an electron. Assuming no initial injection velocity, we can then estimate the field enhancement to be between 20-40 throughout the annealing process, which is within an order of magnitude of enhancement factor of Si nanostructures found in literature. However, this may in reality be less given significant multi-photon ionization as the electrons would have an initial energy of $n\hbar\omega - \phi$, where n photons are absorbed, and ϕ is the work function. We infer that the net red shift of the spectra is due to an overall decrease of field enhancement at the surface of the tips. This could be explained by an increase in radius of curvature at the apex throughout the annealing phases. Beyond the anneal-induced red-shift of the spectra, the peak electron signal increases, and the spectra develop a broad higher energy wing, which later forms a peak at high incident energies after the final annealing phases.

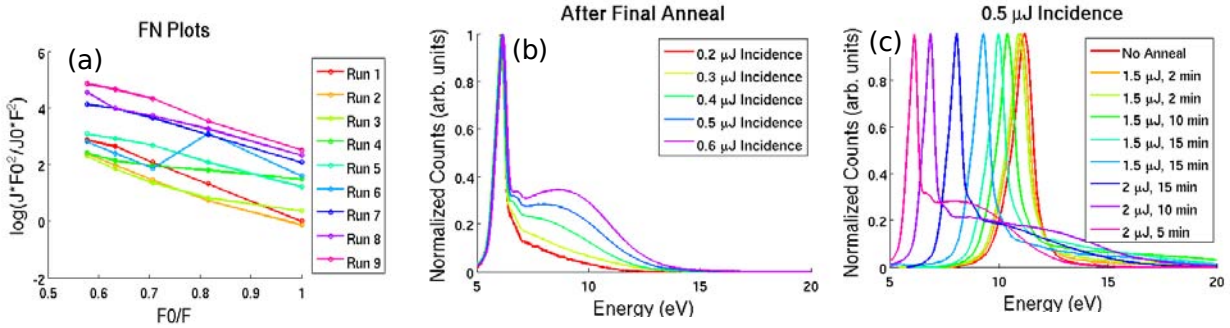

Fig. 2 – Compilation of collected data. (a) Fouler-Nordheim plots of integrated current. The quantities are normalized to F0, the peak optical field at .2 uJ incidence, and J0, the integrated MCP current at .2 uJ incidence after the first run (no anneal). Run 1-9 denotes the annealing step (anneal values and times in (c)). Note the decrease before in integrated current at each field value in terms of anneal time. (b) Spectra collected after final anneal. Notice the development of the large, higher energy peak for higher incident energies, as well as scaling of the cutoff. (c) Spectra collected at an incident energy of .5 uJ after each anneal sequence demonstrating the red-shift of the spectrum along with higher energy peak formation.

A Fowler-Nordheim plot of the data is used to study integrated current yield versus peak optical field strength (Fig. 2). In the plots, J is the integrated MCP current normalized to $J0$, the integrated MCP current of the first spectrum with no anneal. We also define $F0$ as the peak field of the lowest incident pulse energy. One observes a decrease in electron flux before an eventual increase as a function of annealing time for each value of peak field. This follows theoretical results of total current yield when modeling the effects of oxide thickness on a silicon surface[5]. Essentially, as the oxide is decreased, the activation field of the tip decreases. However, at higher field strengths, the slope of the current versus field curve is increased with thicker oxides, resulting in higher currents despite thicker oxides.

The fact that $\Delta E_{kin}/E_{kin} \approx .1$ of the main emission peak was maintained throughout the annealing process, along with the low laser powers needed for emission, both clearly demonstrate the potential of Si FEAs as high-flux near mono-energetic electron sources. Further theoretical and experimental studies are planned for better understanding and characterization of the process.

5. References

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