Nanostructured Silicon Photo-Cathodes for X-Ray Generation

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***Abstract*—We report the fabrication and characterization of ultrafast laser triggered nanostructured silicon photo-cathodes for x-ray generation via inverse Compton scattering. A highly uniform array of ~2200 silicon pillars with 5 µm array pitch, where each pillar is capped by a nanosharp tip, shows stable current emission using 35 fs, 800 nm laser pulses. The cathodes can emit at 3.6 nA average current over 8-million 1.2 pC electron bunches when excited with 9.5 µJ laser pulses with no degradation of the emission characteristic of the cathode, showing that silicon-based photon-triggered cathodes processed with standard CMOS processes and operated at high vacuum can function for extended periods without performance degradation.**

Keywords*— coherent x-ray; field emission; MEMS; multiplexed; photocathode; ultrafast optics

I. INTRODUCTION

Nanostructured cathodes that can be switched at an ultrafast time scale (<1 ns) have applications in free electron lasers and coherent x-ray sources [1]. State-of-the-art ultrafast cathodes are flat surfaces that emit electrons using ultraviolet (UV) pulses, harnessing the photoelectric effect; these devices need ultra-high vacuum to operate and have short lifetime. Photon-triggered field emission cathodes are an attractive alternative to circumvent the shortcomings of UV photocathodes, while providing a direct means of structuring the emitted electron beam. Narrow tip radii distributions are required to achieve high utilization of the field emitter array given the exponential dependence of the field-emitted current on the emitter field factor. For coherent x-ray generation to be possible, the photo-cathode needs to produce a uniform series of nanostructured charge sheets with sufficient charge over an extended period of time.

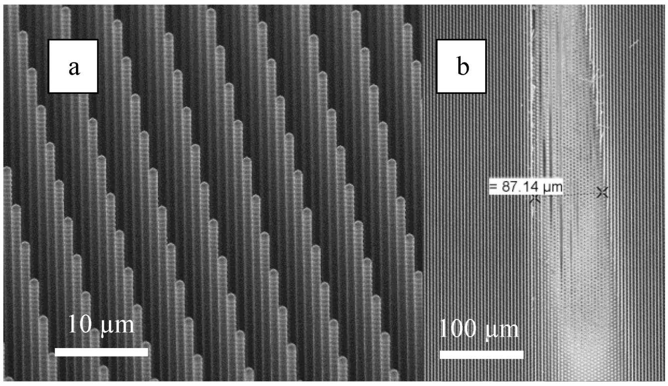

Fig. 1 – (a) SEM of high aspect-ratio single-crystal Si pillars with uniform nanosharp tips. (b) Damage to Si tips after exposed to 20.5 µJ laser pulses.

II. FABRICATION

The cathodes are fabricated from single-crystal <100> n-Si 1-10 Ω-cm wafers. The process flow includes the fabrication of arrays of hard mask features patterned by projection optical lithography and reactive ion etching; each feature of the array is a silicon dioxide disk on top of a concentric silicon nitride disk. The substrate is then deep reactive-ion etched to form arrays of high-aspect-ratio silicon pillars. Next, the substrate is oxidized to further thin the pillars and to create a nanosharp tip on top of each pillar; finally, the oxide and nitride are striped by selective wet processing. The result are massive arrays of pillars (over half a million elements with 5 µm hexagonal packing) capped by tips with 5 nm average tip radius and less than 1 nm standard deviation [2] (Fig. 1a).

III. APPARATUS AND MEASUREMENT PROCEDURE

The cathodes are photo excited using 35 fs 800 nm pulses at a 3 kHz repetition rate from a titanium sapphire laser at 84° glancing angle, inside a vacuum chamber at ~10^{-8} torr. The beam spot floods ~2220 tips. The cathode chip is connected to ground through a pico-ammeter while the anode, i.e., a 0.25" plate 4 mm above the cathode, is connected to a voltage supply (Fig. 2).

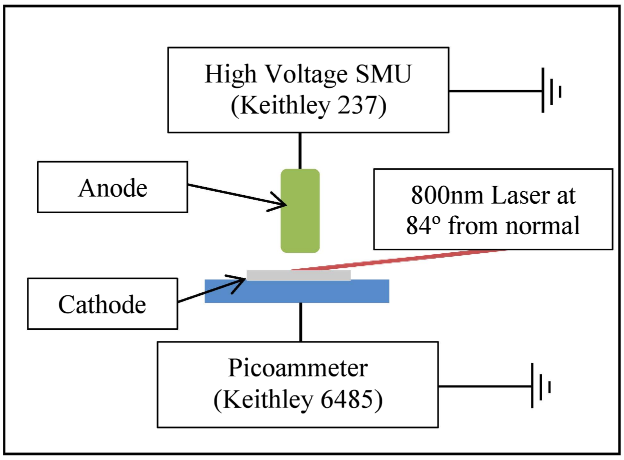

Fig. 2 - Schematic of testing chamber with the cathode connected to ground through a picoammeter (Keithley 6485) and the anode placed 4mm above the cathode and biased by a high voltage source measurement unit (SMU). The laser pulse hits the cathode at a 84° glancing angle.

First, the laser energy is swept from ~30 nJ to 10 µJ using 20 dB and 10 dB neutral density filters, while the anode voltage is kept constant. The signal collected is DC current through the cathode and anode resulting in average current measurements over a series of electron pulses with 3 kHz repetition rate. The current is then converted to emitted charge per pulse by dividing the average current value by the repetition rate of the laser. Data is collected from varied anode voltages and incident energies.

IV. RESULTS

The results from the sweeps are plotted in Fig. 3. At low intensities (<0.1 µJ), the electric field is not strong enough to significantly alter the potential barrier, requiring 3-4 photon absorption for electron emission from the high-aspect tips (power dependence slope of ~3.9 shown in Fig. 3). At laser intensities over 2 µJ, the slope bends over to a ~0.5 power dependence, evidencing a transition to the tunneling emission regime (Fig. 3). This transition has been reported in [2] and [4].

At higher incident energies, the anode bias has a significant effect on the emitted charge. At 9.3 µJ incident energy, the emitted charge is 0.27 pC with 10V anode bias and 1.39 pC with a 1000V anode bias. The electric field from the anode bias is 3 – 4 orders of magnitude lower than the field from the incident laser so there should be no enhancement from increase in anode bias. There are several possible explanations on the enhancement including charge blockage and an increase in the accumulation layer on the silicon surface. When the electrons are emitted in the short time scale, they produce a sheet of charge with the electric field pointing back towards the tips. This field is calculated to be on the same order as the anode bias thus possibility moving this sheet further away to allow for more electrons to be emitted [2]. The silicon emitters are n-type semiconductor with an accumulation layer on the surface interface with vacuum. The increase in anode bias before the laser pulse arrives will increase the available electrons at the surface to be emitted.

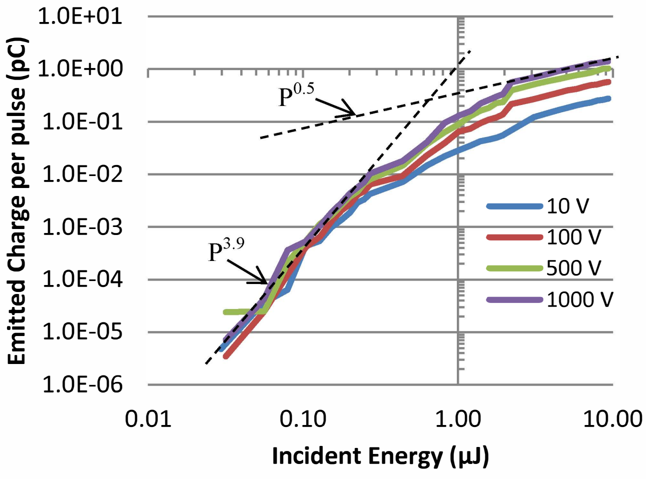

Fig. 3 – Incident laser energy sweeps at different anode biases. The results show multi-photon emission at low energies and then bending over to field emission

Fig. 4 shows three different cathode currents on three different sample locations with the beam being unblocked at time 0 s at an unexposed area. All three curves show stable current emission after 8 million pulses. The lowest curve in Fig. 4 has lower noise than the others and is slightly rising; this is because field emission current is highly non-linear with respect to the photon energy and the activation of the cathode takes longer at lower fields [2]. The highest curve in Fig. 4 shows an average 1.2 pC electron emission (3.6 nA). SEM images taken after the 8 million pulses showed no visible damage. There was no measureable different between the non-exposed tips and the exposed tips from Fig 1a. When the energy of the laser pulses is over 20 µJ, the electric field at the tips becomes too high, which oblates the tips, leaving a ~85 µm by 1800 µm mark in the samples that matches the laser spot size (Fig. 1b).

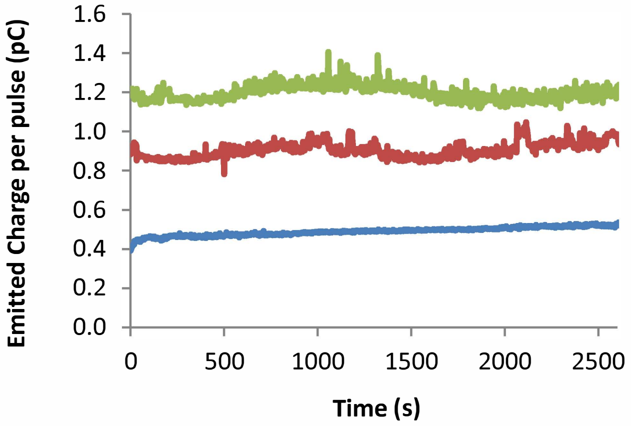

Fig. 4 – Stability of emitted current from the photocathode over time. Top green line is 9.5 µJ with 1000 V anode bias, middle red line is 9.5 µJ with 500 V anode bias and the bottom blue line is 3.0 µJ with 500 V anode bias.

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