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OBSERVATION OF THE FEMTOSECOND LASER-INDUCED EMISSION FROM THE DIAMOND FIELD EMITTER TIPS*

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Abstract

This paper reports results of the experimental observation of emission from single diamond field emitter tips when triggered by an ultra-short laser pulse. It has been proposed that single diamond tip emitters can be employed for production of small tightly focused electron beams for dielectric laser accelerators (DLAs) that accelerate particles using the energy of light produced by infrared lasers. To generate short electron bunches required by DLAs, diamond pyramids may be triggered with a laser. We have recently observed emission produced by a single diamond pyramid when triggered by a laser at different wavelengths from 256 nm to 2000 nm. We have conducted studies with the goal to understand mechanism of the emission. We clearly observed the change in emission mechanism when the wavelength changed from 256 nm to 512 nm. We believe that while the emission at 256 nm is a clear single-photon photoemission, the emission at longer wavelengths is likely the field emission caused by intense electric fields of the laser.

INTRODUCTION

Dielectric laser accelerator (DLA) research gains momentum with the goal of demonstrating an ultra-compact acceleration system with multiple applications. DLAs represent dielectric microstructures powered by lasers with wavelengths ranging from 800 nm up to 2 microns. Accelerating gradients as high as 700 MV/m were demonstrated in DLAs [1,2]. Because of the often sub-micron dimensions of the accelerating structures, one of the most critical needs in the field is to develop ultra-compact high-current-density electron sources, that can preferably be triggered by a laser to simplify the issues of synchronization of the electron beam and the accelerating structure [3]. Our team at Los Alamos National Laboratory (LANL) has proposed to use diamond pyramids, often referred to as "diamond field emitter arrays (DFEAs)" as electron beam sources in DLAs [4]. DFEAs were first introduced by Vanderbilt University [5] and represent arrays of micron-size diamond pyramids with nanometer sharp tips (Fig. 1). They are known to produce electron beams by field emission with a single pyramid tip capable of producing currents as high as 30 µA in a direct current (DC) regime. At LANL we fabricate DFEAs of different configurations and study them on a DC high voltage test stand. In order to understand applicability of DFEAs for production of high current density electron bunches for DLAs, an experiment at Stanford University DLA laboratory was put together in the framework of the Accelerator on a Chip International Collaboration (ACHIP) [6].

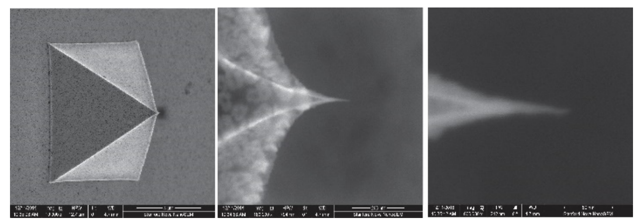

Figure 1: Scanning electron microscope (SEM) images of a diamond nano-tip at different magnifications.

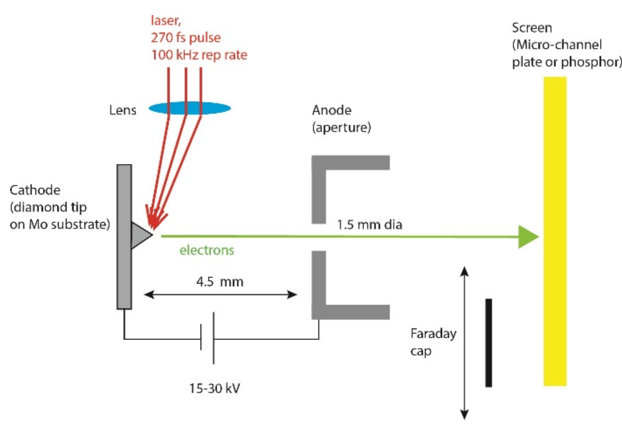

Figure 2: The schematic of the strong-field photoemission test stand.

EXPERIMENTAL SETUP

The experimental setup is illustrated in Fig. 2. The diamond cathode representing an array of 25 diamond pyramids with the size of approximately 22 microns and spaced 400 microns apart was brazed to a molybdenum (Mo) substrate. The substrate was installed on a movable arm that was controlled with a magnetic coil allowing for moving the cathode in two transverse directions for precise alignment of the laser and different diamond tips. The anode represented a metal plate with a small hole in the middle located at a distance of about 4.5 mm from the cathode. The voltage of 15 to 30 kV was applied between the cathode and the anode. Field emission from nano-tips was used to align the particular tip with the axis of the anode. Subsequent strong-field photoemission measurements were

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performed with voltages below the field emission threshold. Different tips on the cathode were illuminated by a laser light which entered the vacuum chamber through a window at the side of the chamber. The wavelengths of the laser light varied in between 256 nm and 2000 nm. The length of the laser pulse was approximately 270 fs, and the repetition rate was 100 kHz. The spot size of the laser on the diamond sample varied between 20 and 40 micrometers. The produced electron beam was imaged on a microchannel plate (MCP) located approximately 40 cm from the cathode. Images on the fluorescent screen of the MCP were captured by the camera. The calibration of the image's intensity versus electron current was performed with intermittent current measurements with the Faraday cup at different MCP gains.

OBSERVATION OF A SINGLE PHOTON EMISSION

In agreement with the expected single photon emission threshold for diamond of about 5.5 eV we observed the photoemission from the sample when excited by a laser at the wavelength of 256 nm. The electrons were generated efficiently at various laser intensities from nano-tips as well as from the flat areas of the nano-crystalline diamond in between the nano-tips. The slope of the yield curve (Fig. 3) was very close to one indicating the single photon photoemission. No apparent signs of the current roll-off even for very high electron bunch charges indicated large emission areas.

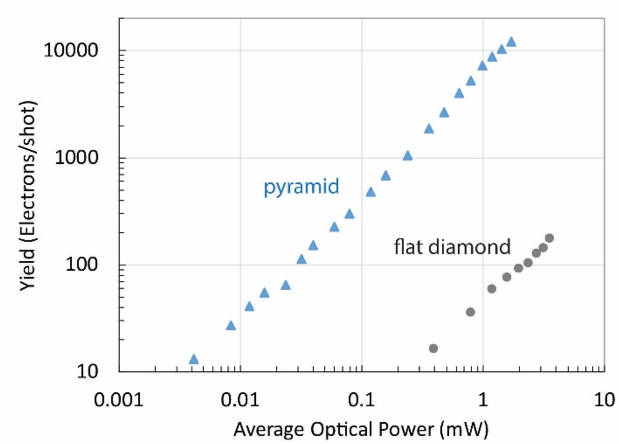

Figure 3: The number of electrons emitted from a diamond nanotip and a flat diamond area when excited by a laser with the wavelength of 256 nm plotted as a function of the average optical power.

OBSERVATION OF A STRONG-FIELD PHOTOEMISSION

When the laser at the wavelength of 512 nm and above was not aligned with a nano-tip, relatively low strong-field photoemission was observed from the flat nano-crystalline diamond. However, when the laser spot strongly overlapped with a pyramid, a distinct beam profile shown in Fig. 4(a) was observed on the MCP screen, identified by up to 4 approximately center-symmetrical lobes. Rotation of the sample around pyramid's axis caused rotation of the emission pattern, and the orientation of the lobes indicated that the pattern was due to electron emission from the sides of the pyramid. Fine-fringed structure was often observed on the lobes with the period approximately proportional to the laser wavelength. Coincidentally, prolonged exposure of the pyramids to the high intensity laser beam caused a specific damage on the pyramids (Fig. 4(c)).

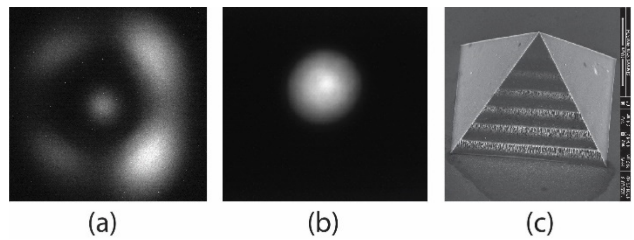

Figure 4: The emission pattern observed on the MCP screen for (a) lower laser intensities; (b) higher laser intensities. (c) The SEM image of a pyramid damaged by the laser light.

Next, the very tip of a pyramid was illuminated with the laser and the dependencies of the emission on the polarization of the laser light were studied (Fig. 5). The polarization dependencies were found to be quite reproducible and qualitatively agreed with the strong field mechanism of photoemission: optical field was significantly enhanced at the sharp tips when the orientation of the electric field coincided with the axis of the tips and more current was produced. However, a fine structure was often observed in the electron beam profile coming from the nano-tip and separate beamlets could be identified in the pattern with somewhat different polarization dependencies, their superposition producing "distortions" in the current-versus-polarization curve shown in Fig. 5. We attribute the fine structure of the beam profile to irregularities of the tip.

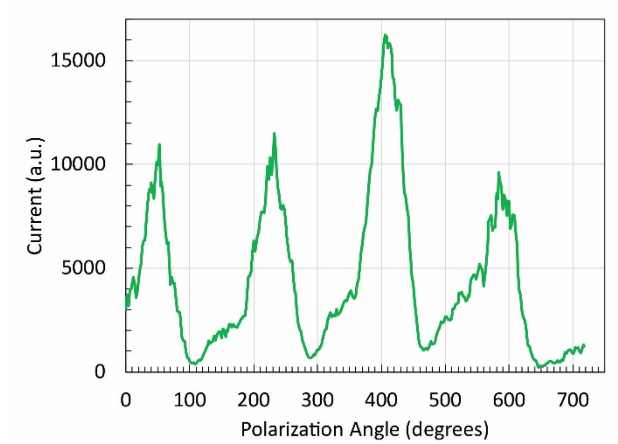

Figure 5: The current measured by the Faraday cup as a function of the polarization angle of the incident laser for the laser wavelength of 800 nm.

The dependencies of the number of emitted electrons on the optical power were studied next for various wavelengths and are shown in Fig. 6 for the particular tip numbered Mo45_1-3. The plotted dependencies look similar in

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shape to those typically observed for the strong-field photoemission. They have a very steep onset followed by a roll-off always observed at yields above 30 electrons per shot, but with three very notable distinctions. First, the electron yield for relatively low laser intensities is high compared to other similar measurements [7]. Second, the low intensity parts of the curves do not reveal obvious power law dependencies (n-photon orders). Instead we observed various slopes with the power order varying between 8 and 12 for wavelengths between 800 nm and 2000 nm with no apparent systematic dependence. Third, the electron yield obtained from different nano-tips followed different power dependencies on the optical power (Fig. 7). The reasons for different low-power slopes measured from different tips at the same wavelength are not entirely clear at this point. The electron yield is assumed to be a function of the peak laser intensity, which depends on loosely defined parameters such as the laser's spot size and shape and the position of the laser spot with respect to the nano-tip and can vary with time and position of the laser. In addition, the different power dependencies may in fact be the result of irregularities of each individual tip's geometry and composition.

The size and shape of the electron beam image on the MCP screen looked distinctly different in the "roll-off" region (Fig. 4 (b)) as compared to the low laser intensity region. At higher laser intensities the fine structure of the beamlets disappeared and all current seemed to originate from around the sharp nano-tip on top of the pyramid with a typical bell shape. We attribute the roll-off and the current saturation to the Coulomb interaction between electrons emitted from the nano-tip and screening of the electric field by their cloud.

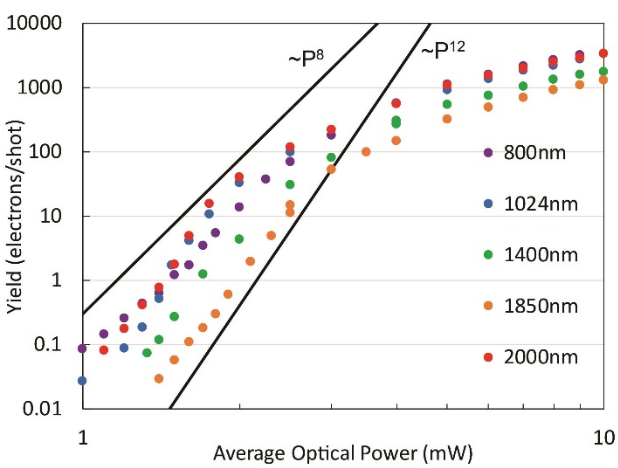

Figure 6: The number of electrons emitted from a diamond nanotip Mo45_1-3 when excited by a laser with wavelengths ranging from 800 nm to 2000 nm plotted as a function of the average optical power.

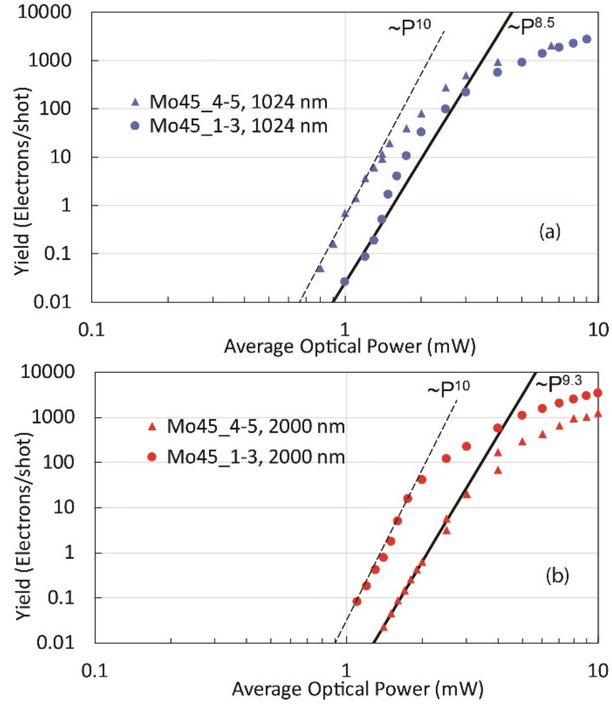

Figure 7: The number of electrons emitted from two different diamond nano-tips (Mo45_1-3 and Mo45_1-3) when excited by a laser with (a) the wavelength of 1024 nm and (b) the wavelength of 2000 nm plotted as a function of the average optical power.

CONCLUSION

In this paper we reported the results of the recent observations of the strong-field laser-induced emission from ultra-nano-crystalline diamond nano-tips. The emission was observed at different wavelengths ranging from 256 nm to 2000 nm. The emission at the wavelengths of 512 nm and above was attributed to the mechanism of the strong field photoemission. Significant bunch charges have been produced in ultra-short pulse lengths below 300 fs. As we continue to improve technology to make sure all tips on an array are nearly identical, we use the remaining variance in nano-tips' curvature radii to qualitatively assess the correlation between tips' geometries and their strong-field photoemissive properties. Results obtained so far are consistent with the hypothesis that higher optical field enhancement would be achieved at sharper tips, leading to stronger emission for the same laser intensity.

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