ELECTRON TRANSPORT AND EMISSION IN DIAMOND

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Abstract

The diamond amplified photocathode has the potential to dramatically increase the average current available from photoinjectors, perhaps to the ampere-class performance necessary for flux-competitive fourth-generation light sources. Electron emission from a diamond amplifier has been observed from hydrogen-terminated diamond, using either photons or electrons to generate carriers. An emission gain of 40 has been achieved using a thermionic cathode and a gain of 6 from amplification of electrons from a photocathode. Very high average current densities (>10 A/cm^2) have been transported through the diamond using x-ray generated carriers. The electron affinity of hydrogen-terminated diamond has been measured to be about -1.1 eV.

INTRODUCTION

One method to reach the average currents required by future light sources may be to use a standard photocathode in conjunction with an "amplifier" to increase the emitted current while retaining the small phase space volume of the photocathode. One such device, based on diamond, has been proposed [1]; this device uses low energy (few keV) electrons to produce carriers in diamond. The diamond is biased such that electrons drift toward the emitting surface, which has a negative electron affinity (NEA) due to hydrogen termination [2]. The electrons are emitted through the NEA surface into the accelerating cavity. As an initial primary electron can produce hundreds of secondaries, this device has the potential to greatly increase the available current for a linac-based source.

Electron emission from diamond has been previously demonstrated using a thermionic electron gun to produce carriers; a gain in excess of 80 has been shown for reflection geometry [2] and a gain of 40 has been shown for transmission (amplifier) geometry [3]. Here we report on recent progress in the development of the amplifier, including the demonstration of a fully functioning amplified photocathode. Current densities >10 A/cm^2 have been generated in the diamond using x-ray generated carriers, and the emitted electron energy spectrum has been measured with angle-resolved photoemission spectroscopy (ARPES).

AMPLIFIED PHOTOCATHODE

The demonstration of a diamond amplified photocathode was performed using the apparatus shown in figure 1. This device consists of a copper photocathode, a diamond amplifier and a collection anode. The amplifier is an element-6 (e6) electronic grade single crystal, 4.15x4.15 mm^2, 0.21 mm thick, with a [001] surface normal crystalline orientation. One face of the diamond is metalized with sputtered Ti, then Pt (nominally 15 nm Ti, 30 nm Pt). The opposing face was hydrogen terminated via plasma hydrogenation in the diamond growth chamber at the Center for Nanoscale Materials.

The metalized surface of the diamond faces the photocathode; there is a 0.3 mm vacuum gap between hydrogenated face of the diamond and the copper anode. This gap is set by precision spacers (much longer than the gap to minimize surface conduction). The entire anode-and-diamond assembly can be baked via an internal heater to 230 C – this is necessary to remove adsorbed water from the hydrogenated surface of the diamond and recover the NEA surface. There is a 1 cm gap between the photocathode and the diamond, allowing off-axis illumination of the photocathode by a KrF excimer laser (λ=248 nm, pulse FWHM = 4 ns). The laser spot on the cathode is ~1 mm diameter. The cathode is biased to -5 kV DC; this determines the primary electron energy. The metalized face of the diamond is grounded through a diagnostic equipment, either an electrometer (Keithley 6517) or an oscilloscope. The anode is biased with a pulsed HV supply (~4 kV amplitude, 1.3 μs duration). The timing and repetition rate of the laser and the pulser were controlled via a DG535 delay generator (Stanford Research). The pulser was run at 30 Hz; the laser is run at the same repetition rate or at a higher rate.

When the laser arrival at the cathode coincides with the HV on the anode, primary electrons from the photocathode are accelerated to 5 keV to strike the metalized face of the diamond. The primary electrons lose a significant amount of energy in the metal layer (~3 keV); their remaining energy is used to produce electron-hole pairs in the diamond via electron-electron scattering. The electrons drift toward the hydrogenated face of the diamond under the influence of the field produced by the voltage on the anode. In the absence of charge trapping/polarization effects in the diamond, the field in the diamond with a 4 kV bias is 2 MV/m (with a field of 11 MV/m in the vacuum between the diamond and the anode).

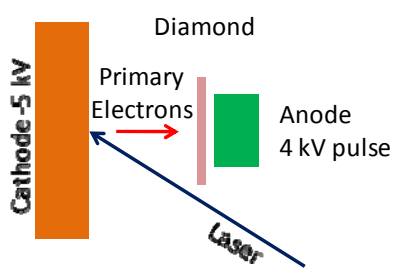

Figure 1: Amplified Photocathode

Due to the modest field (~0.5 MV/m) in the gap between the diamond and the photocathode, the primary charge was limited to ~15 pC per laser pulse, or ~0.45 nA of average current at 30 Hz, to avoid space charge. This charge/current was measured on the diamond when the anode bias was off as a "negative" signal, representing charge arriving onto the diamond electrode. Initially, the laser and the anode pulser were operated at the same frequency (30 Hz); in this configuration the signals remained negative. This suggests that more electrons were arriving at the diamond than leaving – the "gain" (defined as the ratio of the emitted current to the incident current) was much less than unity. When the laser was operated at 60 Hz, a gain significantly in excess of unity was observed, both in "current" mode (using the electrometer) and in "pulse" mode (observing the bunches on the scope). We believe the "additional" laser pulse during the time while the anode bias is zero allows for the neutralization of trapped charge within the diamond. The energetic primary electrons produced by this "off-cycle" laser pulse still create electron-hole pairs in the diamond. The holes drift under the influence of the field built by the trapped charge, eventually neutralizing the traps through recombination. No significant improvement was observed by further increasing the laser repetition rate, suggesting that a single additional bunch of primary electrons per "on-cycle" was sufficient to remove the trapped charge.

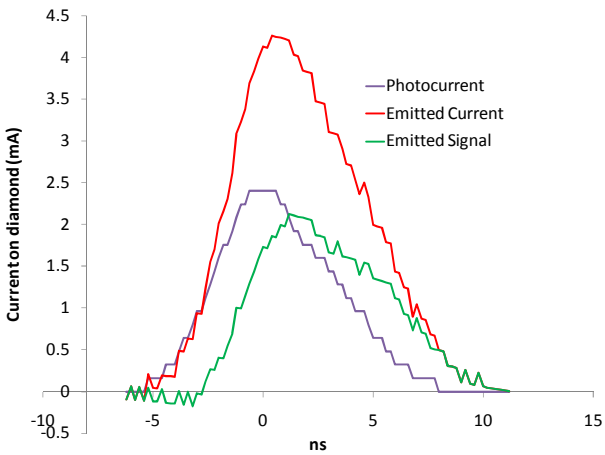

Figure 2: Emission current in pulse mode.

Figure 2 shows the gain measured in "pulse" mode on the scope. Here, the purple photocurrent line has been inverted; this is the primary charge bunch measured on the diamond. It is broader than the 4 ns laser FWHM due to the photocathode-diamond gap transit time. The green emitted signal line shows the result with the anode bias at 4 kV; here the pulse is positive, indicating a net loss of electrons from the diamond (amplification). The actual emitted current is the sum of the (inverted) primary pulse and the emitted signal (this gives a gain of ~2 for the data shown). The peak of the emitted current is delayed with respect to the photocurrent peak – this delay should represent the time required for electrons to cross the diamond. In reality, this delay is shorter than it ought to be based on the electron saturation velocity in diamond (it should be ~1.5 ns for this diamond). This discrepancy is likely caused by trapping of charge from the front of the primary bunch affecting the propagation and amplification of later portions of the bunch. If electrons are trapped in the diamond, the field within the diamond is reduced. When the field in the region near the metallization is reduced, more carriers are lost to diffusion into the metal layer, reducing the effective amplification of the device, and effectively shortening the emitted pulse.

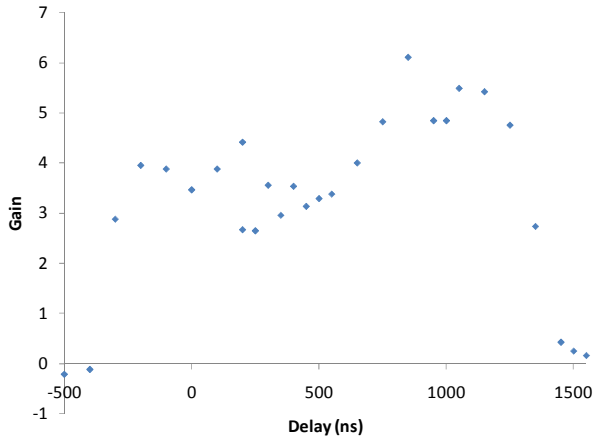

Figure 3: Gain in current mode vs. laser delay. The zero of delay is arbitrary.

Figure 3 shows the gain in "current" mode as a function of the delay between the laser and the anode voltage pulse, using the electrometer as the diagnostic. This gain is 3-6, suggesting that there may be some electron emission from the diamond after the initial "pulse" (this would be measured in the second-long integration time of the electrometer, but would not be observed in the pulse response above). Such delayed electron emission could be due to tunneling of charge trapped on the surface, or emission due to bombardment of the surface by ions (which could be desorbed from the anode by the initial secondary electrons).

Overall, the gain observed in this measurement is significantly lower than would be expected. There are at least two reasons this could be the case. First, previous successful demonstrations of gain with thermionic electron guns have used peak primary currents of under a μA, while the peak current in this case is several mA. The higher the current, the faster the charging will occur. Second, the hydrogen-termination may not be ideal on the sample used; this could lead to a larger surface barrier and more surface charging.

HIGH CURRENT DENSITY

To test the current density required for the electron amplifier, a focused "white" x-ray beam from the X28C beamline at the National Synchrotron Light Source (NSLS) was used to generate carriers in a diamond. This allows access to a range of flux values through variable focusing of a mirror and the use of aluminum filters of various thicknesses (0.08-4.5 mm). An ion chamber

(filled with dry N_2 gas) is used for calibration of the strongly attenuated beam; a copper calorimeter (3.44 g) is used for calibration of beams which saturate the ion chamber. Figure 4 shows the linearity of the diamond current with flux for a diamond metalized with Pt on both surfaces. An average current of 85 mA was generated in an area of 1.1x0.6 mm^2, corresponding to an average current density of 13 A/cm^2 – roughly an order of magnitude higher than is envisioned for a diamond amplified cathode operating at a storage-ring equivalent current (~0.5 A). The peak current density in this case is ~60 A/cm^2, also above that anticipated for a storage-ring equivalent source. The energy required to create an e-hole pair (w) is 13.4 eV, in line with expectations [4].

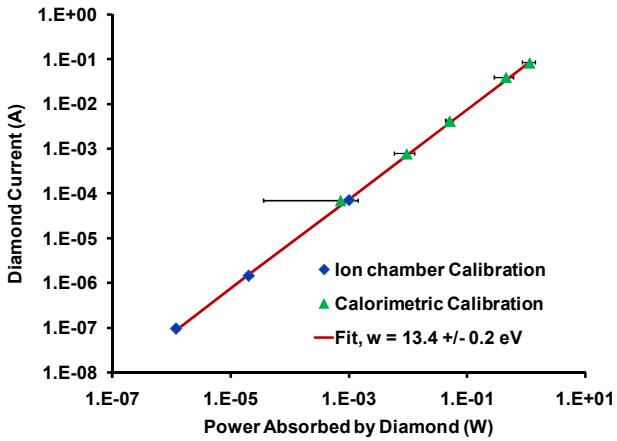

Figure 4: Linearity of current in diamond with respect to absorbed x-ray power.

ELECTRON ENERGY SPECTRUM

The electron affinity and emitted energy spectrum of diamond was measured at NSLS beamline U13UB using ARPES. To avoid surface charging, a heavily boron-doped (conductive) diamond (also from e6) was used. Figure 5 shows the emitted energy spectrum from laser irradiation (6 eV photons) of the hydrogen terminated surface of the diamond.

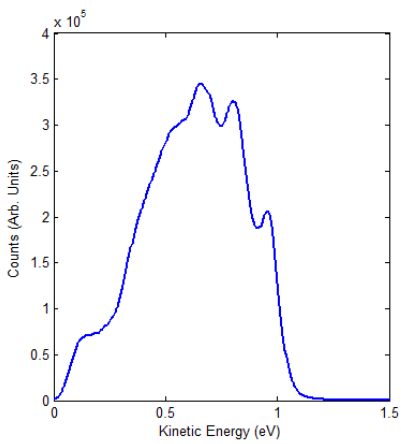

Figure 5: Electron energy spectrum emitted from a hydrogen-terminated, boron-doped diamond.

These near-threshold photons have an absorption length of >1 μm, thus the electrons excited within the material thermalize to the bulk conduction band prior to emission (similar to electrons in the amplifier). The maximum emitted kinetic energy (KE) therefore corresponds to the diamond NEA. Scattering within the band-bending region results in a range of KE down to the vacuum level. This data reveals clear, evenly spaced energy features we believe are related to optical phonon modes within the diamond, and yields a NEA value of ~1.1 eV, in line with expectations. It is possible that the boron doping level of the diamond used in this work results in a significantly narrower band bending region than would be present in intrinsic diamond; this could lead to a narrower energy spectrum for the amplifier.

CONCLUSION

A diamond-amplified photocathode (DAP) has been successfully demonstrated, achieving a gain of 6 (referenced to the incident primary current). The device suffers from significant electron trapping, which screens the applied field and limits the gain. The trapped charge build-up between pulses was successfully mitigated by injecting primary electrons during a period of zero applied bias in the diamond; charge trapping and field screening during the pulse is still an issue.

Charge transport in diamond has been demonstrated at current densities well beyond those anticipated in a DAP. The current remained linear with the incident power, suggesting that internal space-charge effects are not significant at these current densities. The width of the emitted electron energy spectrum of a hydrogenated diamond was measured to be ~1.1 eV using laser ARPES; this may be an over-estimate of the spread which will be achieved in a functioning DAP.

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