Electron Amplification in Diamond

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Abstract. We report on recent progress toward development of secondary emission "amplifiers" for photocathodes. Secondary emission gain of over 300 has been achieved in transmission mode and emission mode for a variety of diamond samples. Techniques of sample preparation, including hydrogenation to achieve negative electron affinity (NEA), have been adapted to this application.

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DIAMOND AMPLIFIED PHOTOINJECTOR

This paper provides an overview of the ongoing effort to produce a diamond amplified photoinjector [1-3]. This injector would produce an electron bunch from a photocathode, accelerate this bunch to a few keV, and pass the beam into a thin diamond slab. The primary electrons lose their energy in the first fraction of a micron of travel primarily via electron-electron scattering, producing electron-hole pairs. The diamond is biased such that the electrons flow to the far side, where they are emitted from a specially-prepared, negative electron-affinity (NEA) surface into vacuum. A diagram illustrating this process is shown in figure 1.

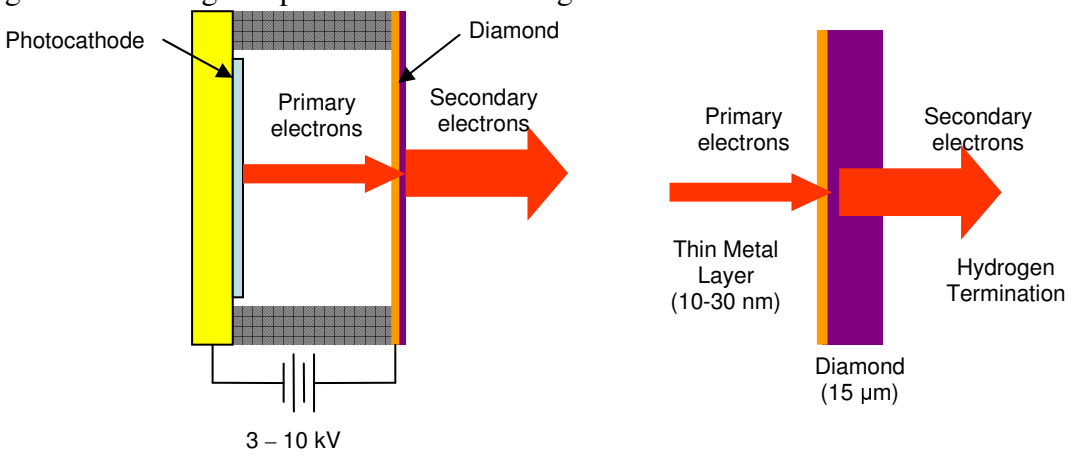

FIGURE 1. Schematic of capsule photocathode (left) and magnified view of diamond window (right).

The diamond acts as a vacuum barrier as well as an amplifier, protecting the cathode from the injector vacuum. The primary electron side of the diamond must be metallized to allow the holes to be neutralized and to provide the accelerating gradient

for the primary electrons. This metallization layer affects the band structure of the diamond near the surface; thus the choice of metal and deposition technique is critical [4]. The emission side of the diamond must be hydrogen (or cesium) terminated to achieve an NEA surface [5]. To address these challenges, a research program has been developed to characterize various diamonds and investigate their performance as secondary emitters. Results for three classes of diamond are presented, and electron gain is characterized in two geometries – emission (electrons emitted into vacuum) and transmission (electrons conducted through bulk diamond).

EXPERIMENTAL ARRANGEMENT

Three types of diamonds were investigated in this study. One was a type IIa natural diamond with a 110 crystalline orientation purchased from UralAlmazInvest. This diamond was 2.6x3x.16 mm^3. Two diamonds were CVD grown synthetic diamonds from Harris International/Element Six (HI/E6). One was polycrystalline electronic grade (typical grain size ~100μm) with dimensions of 5mm diameter, 0.15 mm thick. The other was a 4x4x0.16 mm^3 detector grade single crystal with a 1,0,0 orientation.

Characterization

These diamonds were characterized via FTIR and Raman/Photoluminescence (R/PL). The FTIR spectrum of each diamond is shown in figure 2. The structure of these spectra is characteristic of the diamond lattice, with the exception of the peak at 1282cm^{-1} in the natural diamond spectrum. The amplitude of this peak corresponds to ~30ppm of type IaA nitrogen aggregate impurity, a typical impurity in natural diamond [6]. The synthetic diamond have no observable peaks in the nitrogen region, 1100cm^{-1} and 1300cm^{-1}, implying the nitrogen impurity levels are <1 ppm, consistent with the manufacturer specifications. The R/PL spectra are consistent with these nitrogen levels, and are not shown.

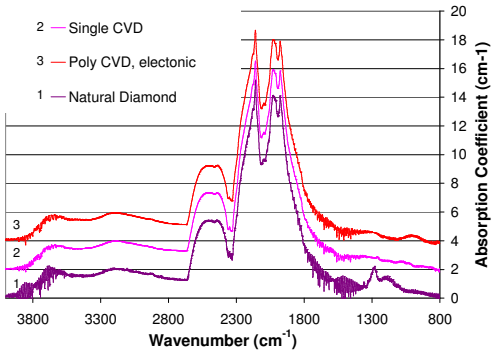

FIGURE 2. IR absorption spectra for the diamonds used.

Preparation of Diamond

In preparation for electron amplification studies, the diamonds were etched in a standard process [2] to remove graphite, metal, organic and inorganic contamination

and establish C-O bond on the diamond surface. For diamonds measured in transmission mode (TM), both broad faces of the diamond were metallized, leaving a rim near the side of the diamond to prevent surface flashovers. The specifics of the metallization vary with each diamond sample, and are detailed in measurements section. For diamonds measured in emission mode (EM), one surface was hydrogenated. This was done by baking the diamond to over 400C in 5nTorr vacuum to break existing C-O bonds on the surface. The sample was allowed to cool, and 1μTorr of H_2 was introduced to the system. A tungsten filament about 2.5cm from the diamond was heated to 1800C to crack the molecular hydrogen. The diamond was exposed to the cracked hydrogen for 20 minutes.

Measurement System

The measurement apparatus consisted of a 2nTorr vacuum system housing an electron gun, and a sample holder. The DC electron gun was capable of emitting electron beams of up to 5keV. The diamond samples were held in a mount (figure 3) that provided electrical isolation of the primary and secondary electrodes.

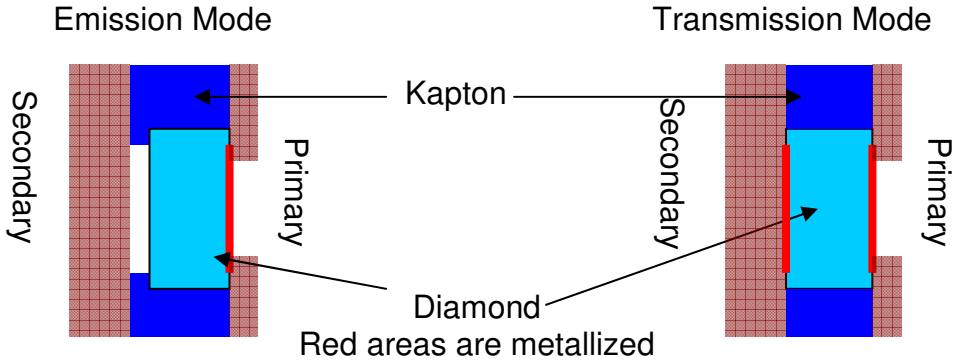

FIGURE 3. Cross-section of diamond mount for emission (left) and transmission (right) mode. In both cases the primary and secondary electrodes are stainless steel.

For transmission measurements, electrical contact was made to both metallized surfaces of the diamond. For emission measurements, a vacuum gap was introduced between the hydrogenated surface of the diamond and the secondary electrode using Kapton insulation. The mount could be cooled via LN_2 lines and included a thermocouple for temperature measurement. The power supplies on both the primary and secondary electrodes were capable of measuring currents of 5nA-1mA. The primary electrode was slightly positively biased to prevent escape of secondary electrons produced by the beam from the metal layer. The secondary electrode was positively biased with respect to the primary. In TM, the field in the diamond was taken to be the potential difference (V_{sec}-V_{prim}) divided by the thickness of the diamond (t_{dia}). In EM, the field in the diamond is:

$$F_{diamond} = \frac{V_{\sec} - V_{prim}}{5.7 t_{vac} + t_{dia}} \qquad (1)$$

Here t_{vac} is the thickness of the vacuum gap, and 5.7 is the dielectric constant of diamond. The measured gain is the ratio of the current measured on the secondary

electrode to the current emitted by the electron gun. The primary electron beam on the diamond was estimated to be ~1mm in diameter.

GAIN MEASUREMENTS

Natural Diamond

The type IIa natural sample was metallized on both sides with 30 nm of Al via evaporation. The electron gain was studied in TM at 293K (figure 4) and 81K (figure 5) for a variety of primary energies and primary currents. For EM measurements (figure 6) the Al was etched and replaced with gold on one face prior to hydrogenation.

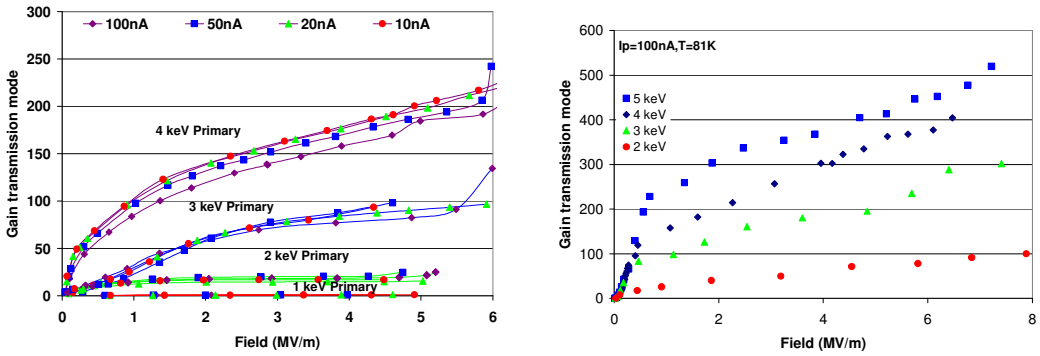

FIGURE 4&5. Left: Gain of natural diamond in TM vs. field in diamond at 293K. Line color gives primary electron energy. Symbols indicate primary current. Right: TM gain of natural diamond vs. field in diamond for primary energies of 2-5keV at 81K with 100nA primary current

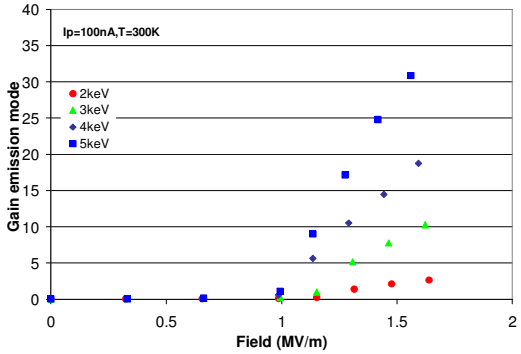

FIGURE 6. EM gain of natural diamond vs. field in diamond for primary energies of 2-5keV at 293K with 100nA primary current.

Polycrystalline CVD Diamond

This sample was measured in EM at 293K (figure 7) and 81K (figure 8). The metallized surface was prepared by evaporating 20 nm of gold after hydrogenation.

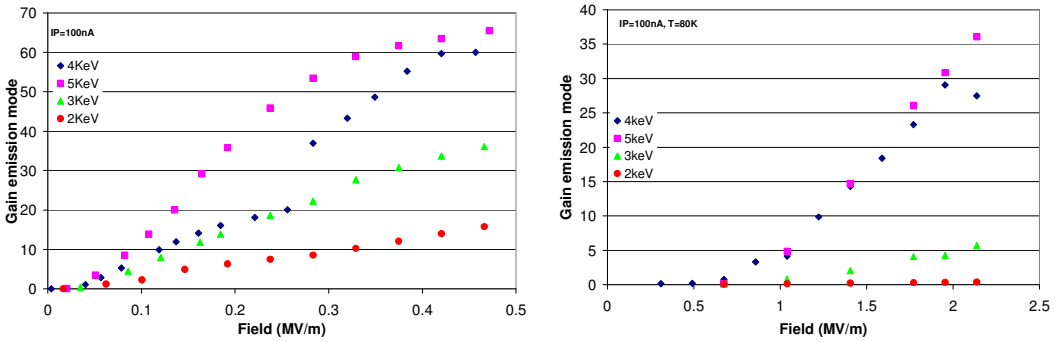

FIGURE 7&8. Left: EM gain of electronic grade polycrystalline CVD diamond vs. field in diamond for primary energies of 2-5keV at 293K with 100nA primary current. Right: Same, at 81K.

Single Crystal CVD Diamond

Two samples of this type were measured, one in transmission and one in EM. The TM sample was metallized on both surfaces by sputtering 5 nm Ti followed by 10 nm of W and measured at 293K (figure 9) and 81K (figure 10). The EM sample was metallized by sputtering 5 nm Ti followed by 5 nm of Pt and measured at 293K (figure 11) and 81K (figure 12).

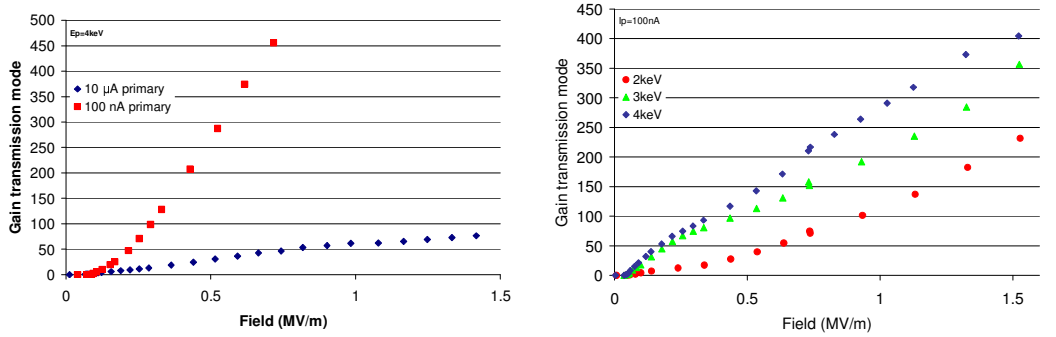

FIGURE 9&10. Left: TM gain of single crystal CVD diamond vs. field in diamond for 4keV primary energy at 293K with 100nA and 10µA primary current. Right: TM gain of single crystal CVD diamond vs. field in diamond for primary energies of 2-4keV at 81K with 100nA primary current.

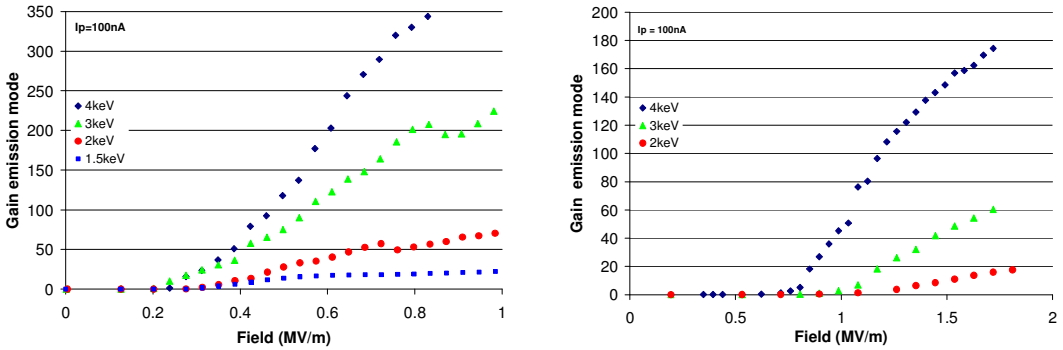

FIGURE 11&12. Left: EM gain of single crystal CVD diamond vs. field in diamond for primary energies of 1.5-4keV at 293K with 100nA primary current. Right: Same, at 81K.

Discussion of Gain Results

Gains of more than two orders of magnitude have been observed for a variety of diamonds, with a variety of metallization techniques. A NEA surface appears to have been achieved via hydrogenation, given the significant gains observed in EM. For low fields, the gain rises sharply with field, perhaps due to recombination of electrons and holes in the initial stages of the transport. Below 1MV/m, the velocity is not yet saturated, and the electrons and holes spend more time in the vicinity of one another, increasing the number lost to recombination. As the field is increased, the electrons and the holes separate faster and thus the recombination is reduced, leading to a higher net gain. Once the field in the diamond reaches ~1MV/m, the velocity is no longer a strong function of field [7]. The gain at low fields is higher at low temperatures (compare figures 4&5), consistent with the increase in mobility of electrons and holes at low temperatures [8]. Recombination is likely the reason the gain in figure 9 is significantly lower for 10μA primary current compared to 100nA. The number of secondaries lost increases with current density, as the probability of recombination scales with the product of electron and hole densities.

There is a field threshold to begin transmission or emission, especially evident in figures 6,7,8,11&12. This could be explained by charge buildup screening the applied field from reaching the electron-hole production region of the diamond, possibly due to poor contact between the diamond and the metallized surface. This is supported by the polycrystalline CVD results – earlier tests on an identical diamond with a different metallization process observed a threshold field of 4MV/m [2], in contrast to figures 7&8. For the EM results, the threshold field may be affected by contamination of the hydrogenated surface. This may be the reason that the EM threshold was higher and gain lower for cooled samples, as the samples acted as cryopumps for the chamber.

The lack of gain for 1keV primary energies (E_p) and the generally low gain at 2 keV suggest an energy loss (E_{loss}) of between 1 and 2keV in the metal layer before reaching the diamond. The increase of the gain at high fields is surprising. Unless additional electron-hole pairs are produced in the diamond, the maximum gain should be equal to the $(E_p-E_{loss})/E_{creation}$, where $E_{creation}$ is the average energy required to produce an electron-hole pair. $E_{creation}$ in diamond is 13eV [9], thus a 4keV primary should have a maximum gain of ~200. All of the TM measurements, and the EM measurements for the single-crystal CVD diamonds, exceed this value at high fields. Monte Carlo modeling has shown that significant avalanche production of secondaries in diamond requires a field of ~100MV/m [7], far higher than the average field in the diamond in these measurements. This may indicate regions of higher field within the diamond, due to charge trapping or band bending near the surfaces.

In general, these measurements suggest that a field in the diamond of 1-3MV/m would be ideal for a diamond-amplified photoinjector. This field is sufficient to nearly saturate the electron and hole velocity (reducing temporal spreading of the bunch) [7,8]. Modeling predicts electrons moving through diamond in this field have an average energy close (within 0.1eV) to the conduction band minimum, leading to a small energy spread in the emitted beam (and thus a small thermal emittance). This field is achievable in an RF cavity (the field in the diamond will be the RF field at the cathode divided by the dielectric constant of diamond). The model and measurements

[7,8] yield an electron velocity of ~1.5×10^5m/s at these fields, requiring the diamond to be thin (on the order of ~15μm) to achieve emission during one RF cycle at 1GHz.

CONCLUSION AND FUTURE PLANS

The secondary yield of several diamond samples has been measured in emission and transmission modes using a DC electron source. Gains of up to 400 have been obtained with 4keV primary electrons with a synthetic single crystal diamond. The field required to obtain these gains is well within the range achievable in a standard RF photo-injector.

Several tests remain to be done. Gain measurements with a pulsed electron source are needed to determine the temporal profile of the emitted bunch. Energy or emittance measurements of the beam are needed to obtain the thermal emittance of the source. A detailed theoretical model needs to be developed, including electron scattering, recombination and avalanche production. Finally, there are significant engineering challenges involved in the fabrication of a diamond capsule photocathode. These include development of a transparent (back-illuminated) photocathode, development of a process to obtain the required diamond thickness, and construction of an actual capsule in vacuum.

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