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In this paper we explore the possibility of using diamond secondary emitter in a high average current electron injector to amplify the current from the photocathode and to isolate the cathode and the injector from each other to increase the life time of the cathode and preserve the performance of the injector. Secondary electron yield of 225 and current density of 0.8 a/cm^2 have been measured in the transmission mode from type 2 a natural diamond. Although the diamond will be heated during normal operation in the injector, calculations indicate that by cryogenically cooling the diamond, the temperature gradient along the diamond can be maintained within the acceptable range. The electron energy and temporal distributions are expected to be narrow from this device resulting in high brightness beams. Plans are underway to measure the SEY in emission mode, fabricate photocathode-diamond capsule and test diamond and capsule in superconducting RF injector.

1. Introduction:

The creation of high average-current, high brightness electron beams is a key enabling technology for a large number of accelerator-based systems, such as ultra-high-power Free-Electron Lasers (FELs), Energy-Recovery Linac (ERL) light sources, electron cooling of hadron accelerators, and many more. In the past decade, an RF injector with an embedded photocathode that is driven by a laser has proven to be an effective source of high brightness electron beams. In extending this performance to high average current regime, the laser-photocathode is arguably the most difficult component of the system. Robust metallic photocathodes that are popular in the RF injectors typically operate at low average current, need UV photons to overcome the work function of the metal and have very low quantum yield making them inappropriate for high average current applications. Semiconductor photocathodes have high quantum yield at IR or visible wavelengths making them an attractive choice. However they suffer from two serious problems: first, they are very sensitive to contamination, and require ultrahigh vacuum conditions during fabrication, transfer and operation. Secondly, the chemicals of the cathode may contaminate the RF cavity, especially a superconducting cavity, degrading its performance. Finally, even with the relatively high quantum yield of these cathodes, the requirements on the laser may prove to be non trivial. In this paper, we explore the possibility of using diamond to isolate the cavity and the cathode from each other as well as enhance the current from the cathode using secondary emission from diamond. The large secondary electron yield from diamond would reduce the primary current and associated laser power significantly and the physical separation of the cavity and the cathode would increase the life time of both the cavity and the cathode. The design of such a system, operating parameters and preliminary experimental results are presented in the following sections.

2. Description of the system:

A schematic layout of the device is shown in Figure 1. The cathode insert containing the cathode and diamond, shown as **b**, is embedded in the back wall of the injector **a**. As shown in **c**, the surface of the diamond facing the

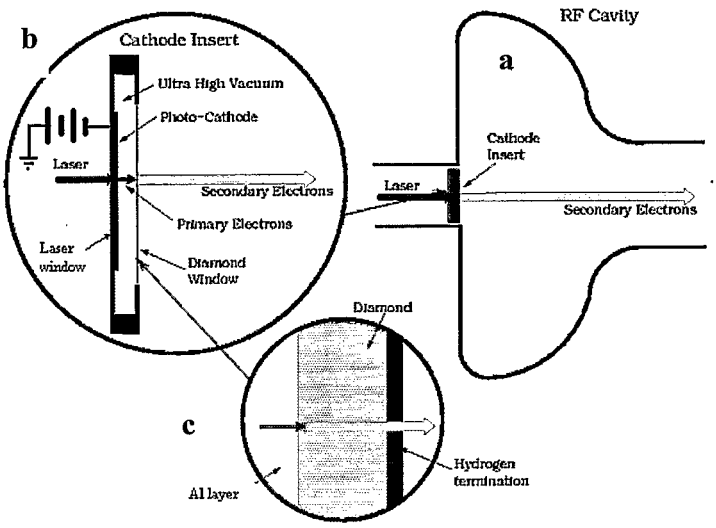

Fig. 1. Schematic of the secondary emission enhanced photoinjector (SEEP)

cathode is coated with a thin metallic layer forming ohmic contact with the diamond. The surface facing the RF cavity is hydrogenated to provide a negative electron affinity (NEA) surface. Up to 10 kV bias is applied between the cathode and the diamond. When a laser hits the cathode from its rear surface, primary electrons are emitted, accelerated by the bias and impinge on the diamond through the metallic layer. Although part of the electron energy is lost in traversing the metallic layer, the system is designed such that the primary electrons enter the diamond with ~ 5keV energy. These energetic electrons produce a large number of secondary electrons in the diamond near the metal layer. These secondary electrons move towards the RF cavity under the influence of the electric field in the cavity and emerge in the cavity through the NEA surface of the diamond to be accelerated by the RF field.

3. **Why diamond:**

The physical and electronic properties of diamond make it a very attractive candidate for a high current, and high current density secondary electron emitter to be used in an RF injector.

- It has the highest saturated electron and hole velocity [1] of $>10^7$ cm/s at fields higher than 2 MV/m field, a gradient that would be present in the diamond in an RF injector. Such a high velocity decreases the transit time of the secondary electrons through the medium and makes it applicable to RF cavity.
- Hydrogenated, boron doped as well as undoped diamond has shown to have negative electron affinity [2,3] increasing the secondary electron yield. Indeed, boron doped, hydrogenated polycrystalline diamond has been shown [4] to be an effective secondary emitter with an enhancement factor of > 80 in the reflection mode.
- The energy distribution of the secondary electrons under low electric field, in the reflection mode is shown to be < 1 eV, centered ~ 4.5 eV above the Fermi energy. This energy distribution is larger than the thermal distribution of the electrons, leading one to conclude that the escape time is smaller [5] than the electron-phonon relaxation time of 10^{-12}-10^{-13} s [6]. The secondary electrons energy distribution traversing the diamond will be the result of equilibrium between two processes. On one hand, the electric field pumps energy into the electrons and the elastic collisions randomize this energy. On the other hand the inelastic collisions remove thermal energy from the electrons and they tend towards the lattice temperature. This process is calculated below, and results a low electron temperature of about 0.4 eV and a temporal width of

~1 ps, or with a slightly larger energy distribution, but narrower temporal width. In either case, the brightness of these electrons will be very high.

- Transport of low energy electrons in the conduction band through diamond has been shown to be very efficient [7]
- Thermal conductivity of diamond is approximately 20 W/cm*K at room temperature and even higher at LN2 temperature [8]. Dissipation of heat generated by the high-energy electrons as well as the high current becomes manageable with such high conductivity.
- The hardness of diamond is highly desirable in terms of mechanical considerations.

4. **Design criteria:** The design parameters are set by the operational requirements of the application. We plan to operate in two modes: In the high charge mode, we require electron bunches of ~ 20 nC charge in ~ 20 ps from a spot size of 8 mm diameter at a repetition rate of 9.4 MHz. In the high current mode, we need electron bunches of 1.4 nC charge in ~20 ps duration from a spot size of 5 mm diameter at a repetition rate of ~350 MHz. Three parameters dictate the physical dimensions of the diamond i) the need of electron bunch to traverse the thickness of the diamond during the accelerating cycle of the RF, ii) the ability to dissipate the heat generated at the diamond by the electron beam and the RF, and iii) the ability to support ~ 1 atmosphere pressure differential across the face of the diamond.

4a. **The heating of the diamond:** The heat sources for the secondary emitter are:

- The power dissipated by the primary electron.
- The power due to secondary electron traversing diamond under strong RF field.
- Power from the electron replenishment current generated on metal film.
- RF power on the metal film.
- The movement of the impurity induced charge carriers in the diamond conduction band in the strong RF field.

There is also the power from electron replenishment in the diamond. As the replenishment distance is very small (~1μm), this effect is ignored.

A FORTRAN code was written to include all the factors discussed above and simulate the temperature distribution in diamond. The criterion is that the maximum temperature in diamond cathode be well below 1000°C to avoid significant Hydrogen desorption from the surface [9]. Simulation results of temperature distribution along the radius, from the center of diamond (R=0) to the edge, for 20 nC/bunch at 9.4 MHz repetition rate from 10 mm radius spot is shown in Figure 2. Input parameters were: primary electron energy of 10 keV, the thickness of the diamond window of 30μm, the metallic layer of 800nm of aluminum, the peak RF field on cathode E_0=15MV/m, and secondary electron yield (SEY) of 300. The temperature on diamond edge is fixed to 80K (assuming Liquid Nitrogen (LN2) cooling) and the primary electron pulse length is 10deg. The dependence of the temperature on the radius is shown for different cathode radii. The powers from different sources for different spot size are listed in table 1

Table 1: Power in W from different sources for three different spot sizes

R	**10mm**	**12.5mm**	**15mm**
Primary	6.3	6.3	6.3
Secondary	7.6	7.6	7.6
RF	7.5	20.0	48.6

Replenishment	0.042	0.046	0.054
Total	21.4	33.9	62.5

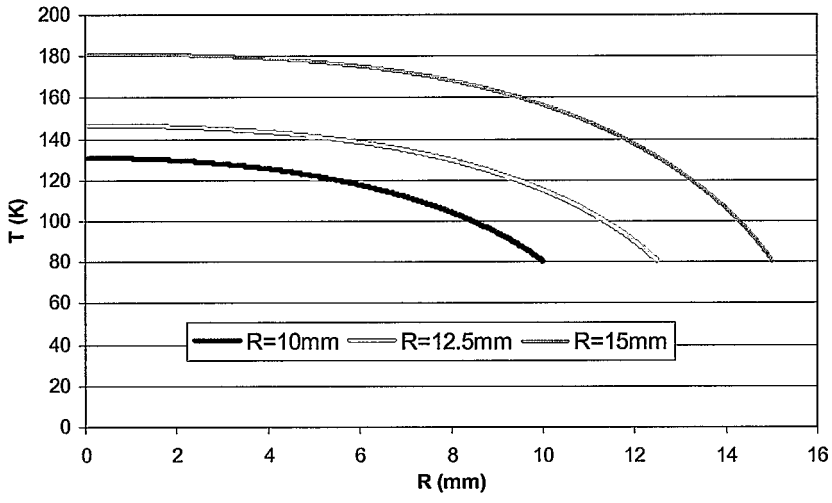

Fig. 2. Thermal distribution along the radius of the diamond for different electron beam spot sizes. Other parameters are specified in the text

As can be seen from the Table 1, the heat is dominated by the contribution from the RF when R>12mm. However, even with a radius of 15 mm the temperature of the diamond is still below 300 K

4 b. Transit Time and Temporal Spread:

The transit time of the electrons must be considered in an RF gun application, since this transit time appears as a delay between the arrival time of the primary electrons and the emergence of the secondary electrons into the gun. During this time the phase of the RF field is advancing and the various calculations must take this time dependence into account.

For low emittance of a beam from the RF cavity, the beam initial phase on cathode is typically between 30degrees to 50 degrees depends on the field strength in the cavity and the cavity geometry. The electrons mostly drift in saturated drift velocity under RF field. For the known saturated drift velocity of 2.7×10^5 m/s which is independent of temperature, the time of flight thorough a 30 micron thick diamond is 110ps, or about 28 degrees of phase at 703.75 MHz, a reasonable number.

Another important consideration is the spread in the time of arrival of the secondary electrons at the far side of the diamond window. Most applications of electron guns place an upper limit on the final pulse width. There are two mechanisms that have to be considered.

One is the random walk due to the thermal energy; the other is the space-charge induced bunch spread. In the random walk part of the problem, the mean free path of the electrons must be considered.

At very low energy most of the momentum modification of electrons takes place through elastic collisions. The elastic cross-section can be estimated by Mott's formula, the total cross-section of electrons under 10 eV is about $\sigma=10^{-15}$ cm^2. The number of elastic collisions is about:

$$Nela = \sigma \times \frac{L}{A^3} = 1.76 \times 10^5 \quad (1)$$

where L is the diamond thickness = 30 micron and A=0.178 nm is the atom radius of diamond. If one assumes that after 10 times of elastic collisions the momentum is randomized, then the number of times that the electron may be stopped by elastic collision is about:

$$Nstop(ela) = 1.76 \times 10^4 \quad (2)$$

The number of inelastic collisions is about:

$$Nstop(ine) = L / \lambda_i \approx 800 \quad (3)$$

So, the number of times that electrons may be stopped by inelastic collisions can be ignored. The broadening is about:

$$\Delta T \approx T / \sqrt{N_{stop}(ela)} \approx (L / V_d) / \sqrt{N_{stop}(ela)} \approx 0.7 \text{ ps.} \quad (4)$$

Thus, the broadening due to thermal random walk of the electrons can be assumed negligible.

As for the effect due to space charge, the drift velocity of the electron is constant for electric fields > 2 MV/m. Therefore as long as the space charge force is much less than the RF field, the temporal spread due to the space charge in diamond can also be ignored. The temporal spread comes mostly from the straggling of the primary electron in the diamond. Assume the primary electron energy is 10 keV, the temporal spread is estimated to be about 3ps.

4 c. Sample quality:

The choice of the crystalline orientation and impurity level of the diamond are important for the ultimate performance of the device. The traps introduced by the impurities and the grain boundaries affect the performance of the diamond significantly. The most important impurities in diamond are donor/acceptor type impurities such as Boron (p-type) and Nitrogen (n-type). Impurity has three main effects: heating of diamond due to ionization of impurities, trapping of secondary electrons and field shielding. Nitrogen impurity has activation energy higher than 1.7eV and is hard to ionize at room temperature. The boron impurity has an activation energy ranges from ~0.1eV to ~0.37eV depending on the doping concentration and therefore very easy to ionize. Hence, the boron concentration needs to be much less than 1ppm to reduce its contribution to the heating of diamond. The electron/hole trap centers trap the charge carriers reducing the SEY. In addition, they generate space charge fields that shield the secondary electrons from the external RF field modifying the electron transport. Furthermore, the delayed release of the trapped charge also distorts the time evolution of the secondary electrons. Since the grain boundaries concentrate charge carrier traps and cause similar detrimental effects, it is desirable to use high purity single crystal diamond. At the very least, grain sizes > 10 micron are desired. It has been shown that [111] can be effectively hydrogenated to result in a NEA surface leading to high SEY.

4d. Metallic coating:

The metal layer is used to replenish the secondary electrons and provide the RF current. Good Ohmic behavior at the metal vacuum interface and metal diamond interface are necessary to minimize the heating of the diamond and the metal and to reduce nonlinear current evolution. One would like to use a material which has as high an electrical conductivity (σ) as possible to reduce the resistance of the film. Also one would like the material to have a long Range of Continuous Slowing Down Approximation (RCSDA) parameter to reduce the energy loss of

primary electrons in the metal film. Possible choices are aluminum (Al), Copper, Silver or Gold deposited on Ti/Pt that forms ohmic contact with diamond. We will assume aluminum to be the metal layer for subsequent calculations. Primary electrons that incident on the vacuum-Al interface with 10 keV energy emerge with ~ 4 keV after passing through in 800 nm Al layer, still sufficient to produce significant SEY. Although the aluminum thickness is much less than the RF skin depth (3.1μm) at 703MHz, most of the field is blocked by this layer [10] and strong RF current will pass through the Al film. This makes a thick, highly conducting film very important.

5. Experimental measurements:

In order for the device to work, several performance criteria need to be met. The primary electron source needs to operate in transmission mode and deliver mA level currents reliably and over a long time. High SEY, efficient transport of the secondary electrons to the opposite face, efficient emission into vacuum, design and fabrication of the cathode insert, and survivability of the diamond as well as the cathode insert in cryogenic, high RF field environment need to be demonstrated. In the following sections we present the experimental results addressing some of these issues.

5a. Secondary electron yield (SEY) in transmission mode:

As a first step in achieving SEE (secondary electron emission) from the diamond sample we have measured the SEY (secondary electron yield) in various diamond samples. The best results were obtained so far with a natural diamond of class 2a. The test setup for measuring SEY is schematically shown in Fig.3. The diamond is coated on both sides with 30 nm thick aluminum. The stainless steel (SS) plates, which are isolated by kapton films are connected to the aluminum films. They are mounted to a sample holder and placed in a vacuum system. The electrodes are connected to the SS plates and are led out of the vacuum so that one can apply voltages on the aluminum films and measure the currents. The primary electrons are emitted from a 0~5keV electron gun. The primary electrons strike the front side (right side) of the diamond with current ranging from 0 to 10μA. The minimum spot size of the primary electron beam is less than 1mm in diameter. The transmitted electron and hole current through the diamond can be measured at the SS plate on the rear side of the diamond by appropriate biasing of the electrodes.

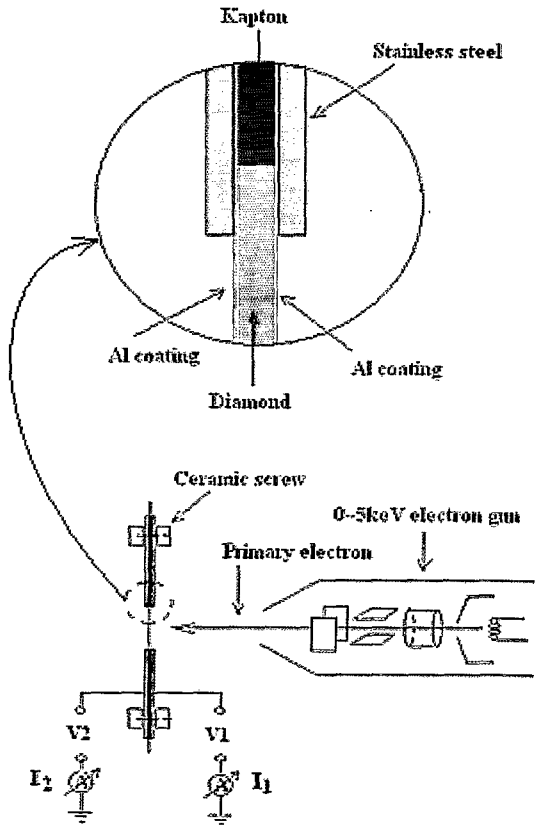

Fig 3. Schematic of the experimental arrangement to measure secondary electron (or hole) transmission yield.. V1 and V2 are floating power supplies ranging from-5kV to +5kV independently

The sample for these measurements was a rectangular, natural type 2a diamond, with lateral dimensions of 3x2.64mm^2 and 160 micron thickness with a modest nitrogen concentration of about 60 ppm (1.3x10-19 /cm^3). Although no other contaminants atoms were reported, their presence can not be rule out. The diamond was inspected with a microscope and was verified to be of good crystal quality.

Figure 4 shows four plots of electron transmission gain through the diamond at room temperature for a constant primary current of 20 nA and four primary energies: 1, 2, 3 and 4 keV. It is obvious that the maximum gain decreases fast as we decreases the primary electron energy. At electron energy of 1 keV the gain disappears because the low energy electrons are totally absorbed in the aluminum coating. For higher primary electron energies, the energy loss in the aluminum layer is estimated to be ~ 1.5 keV. One also notices that the high gain curves do not show the saturated gain property at high field gradient. The slope of the curve at high field gradient increases as the current through the diamond increases. This may be due to the extra current induced by impurity ionizing.

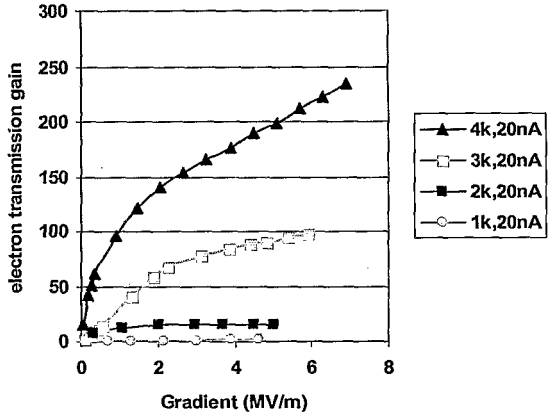

Fig. 4. Electron transmission through the natural diamond for constant primary current of 20 nA at room temperature and primary energies of 1, 2, 3 and 4 keV

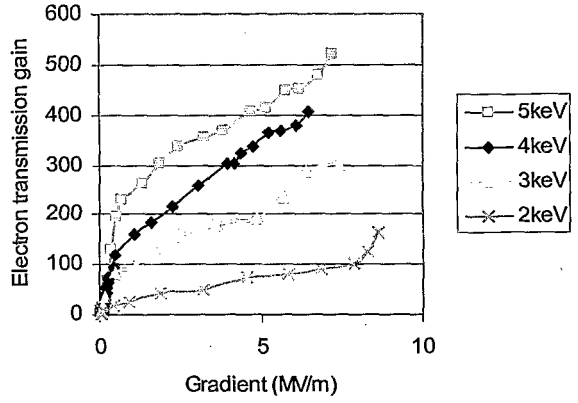

Fig. 5. Electron transmission through the natural diamond for constant primary current of 20 nA at 80K and primary energies of 2, 3, 4 and 5 keV

Figure 5 shows the plots of electron transmission gain for constant primary current of 20nA at a temperature of 80K. Even at low temperature we still get very high gain. Similar to the room temperature case, at high current through the diamond, the gain is higher than one expects due to the impurity atoms ionizing. The clear bend on each curve indicates the depletion of secondary electron-hole pairs generated by the primary electrons. As expected, the gain at this bend location scales linearly with the primary electron energy entering the diamond. SEY as high as 225 has been obtained in this regime. Figure 6 shows performance of this sample when irradiated with large primary current. Maximum current of 0.58 mA (limited by the power supply) and current density of 0.8 A/cm^2 has been generated from this sample.

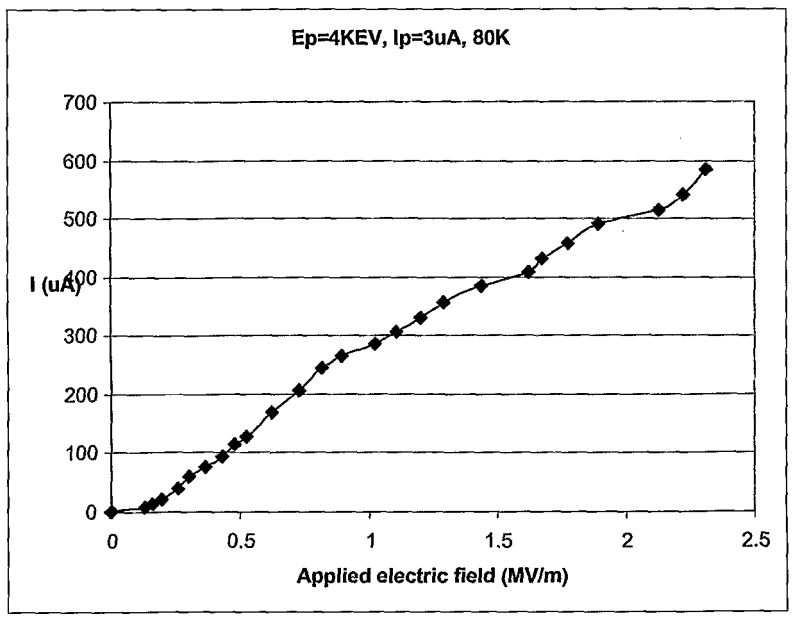

Fig.6. SEE with 3 microamp, 4 keV primary current at 80 K

Efforts are currently underway to test different diamond samples, to develop ohmic contact on one face of the diamond and to hydrogenate the opposite face and to measure the SEE in the emission mode. In addition, several processes are being tested for the fabrication of the capsule.

6. Conclusion:

In conclusion, preliminary theoretical and experimental investigations indicate that diamond as an electron amplifier in an electron gun shows great promise. Secondary electron yield as high as 225 and current densities of 0.8 A/cm^2 have been measured from type 2a natural diamond in the transmission mode. Thermal and energy distribution calculations show that high average current, low emittance electron beams can be produced with LN_2 diamond. Future plans include measurement of SEY in emission mode, fabrication of photocathode-diamond capsule and testing diamond and capsule in superconducting RF injector.

7. Acknowledgement:

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