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diamond amplified cathode*

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*Presented at the Particle Accelerator Conference (PAC09)  
Vancouver, B.C., Canada  
May 4-8, 2009*

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# FIRST OBSERVATION OF AN ELECTRON BEAM EMITTED FROM A DIAMOND AMPLIFIED CATHODE\*

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## Abstract

We observed, for the first time, the emission of an electron beam from a hydrogenated diamond in the emission mode on a phosphor screen. Our experimental device is based on the following concept: the primary electrons of a few keV energy generate a large number of secondary electron-hole pairs in a hydrogenated diamond, and then the secondary electrons are transmitted to the opposite face of the diamond and emitted from its negative-electron-affinity (NEA) surface. Under our present conditions, the maximum emission gain of the primary electron is about 40, and the bunch charge is  $50\text{pC}/0.5\text{mm}^2$ . Our achievement led to new understanding of the hydrogenated surface of the diamond. We propose an electron-trapping mechanism near the hydrogenated surface. The probability of electron trapping in our tests is about 70%. The hydrogenated diamond was demonstrated to be extremely robust. After exposure to air for days, the sample exhibited no observable degradation in emission.

## INTRODUCTION

A few years ago, our group first introduced the concept of the Diamond Amplified Photo-cathode [1]. Thereafter, we tested it in many experiments [2]. The most remarkable observations and achievements in these early-stage experiments were the following:

- Using single-crystal, high-purity, synthetic diamonds greatly reduces electron and hole trapping in the diamond's bulk. This led to our observation of a large gain in transmission-mode measurements even at very low fields across thick diamonds.
- Within the practical range of applications, the dependence of the gain on the field across the diamond did not vary with the primary electron density.
- The saturation gain is independent of temperature.
- Diamonds are very robust and can handle very large current densities.

These experiments showed that in single-crystal, high purity diamonds, the secondary electrons can easily reach the hydrogenated surface (H-surface). We then attempted to measure the fraction of the secondary electrons emitted from diamond. In the device we constructed, the diamond's emission surface was hydrogenated, and there was a gap between it and the anode plate. We applied a DC field between the anode and the diamond's metal coating, such that secondary electrons can be emitted from the H-surface. Unfortunately, in these initial experiments, the emission gain was poor; in our early measurements we never observed directly an image of the emission beam on a phosphor screen.

## THE MODEL

At first, we thought that the poor emission gain we measured was due to poor hydrogenation. Consequently, we continually improved the hydrogenation processes, by purifying the hydrogen gas, improving the vacuum, etc. Additionally, we established a clean space to assemble the samples, so reducing the possibility of contaminating their surfaces during the exposure to air.

Most significantly, we proposed another possible mechanism to explain the poor emissions in our previous measurements. Fig.1 illustrates this new mechanism.

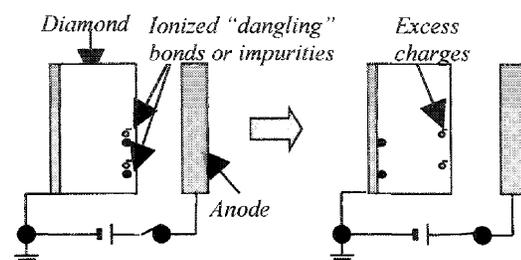


Figure 1. Schematic diagram for the shielding due to impurity/dangling bonds

We postulated that hydrogenation is imperfect and, therefore, dangling bonds and impurities inevitably remain on the H-surface. They may be activated thermally to generate excess charges in the presence of an external field. The density of these charges is proportional to temperature; these excess charges built over time on the H-surface shield the external field, such that the field inside diamond decreases with time. This process continues until either the field is completely shielded, or all the dangling bonds and impurities are dispelled. The second limit is very high even if the portion of the dangling bonds and the impurities on the H-surface is very small. For example, assuming 0.1% coverage of dangling bonds and impurities, they are enough to shield an external field as high as a few hundred MV/m if they all become activated. In other words, even without the primary electrons, practically any DC external field will be shielded completely with time. This was the most important reason why we did not have good emissions in the previous measurements where we always applied a DC field; we termed this mechanism the shielding due to impurity/dangling bonds.

This shielding can be measured experimentally. We designed a circuit that accurately controls the delay time ( $T_{\text{Delay}}$ ) between turn on times of the high voltage pulse and the beam pulse. Then, we measured the secondary electron gain at the beginning of the primary beam pulse ( $G_{\text{on}}$ ). The primary electron beam served as the sensor of the electric field in the diamond.

\*Work supported by the U.S. Department of Energy

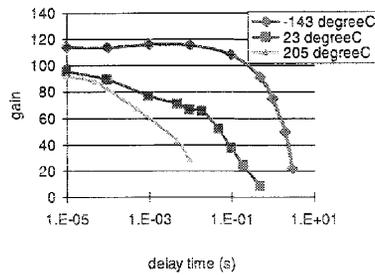


Figure 2: Gain vs. delay time at various temperatures.

The gain decreases as the delay time increases due to shielding of the DC field. As temperature falls,  $G_{on}$  remains constant longer because the ionization density decreases at lower temperatures, and the DC field's shielding slows down. In principle, this measurement can be used to determine the hole density on the H-surface at a certain temperature; therefore, it affords a parameter indicating how good is the hydrogenation.

### EXPERIMENT

The understanding we gained in these experiments led us to a new experiment, schematically shown in fig.3

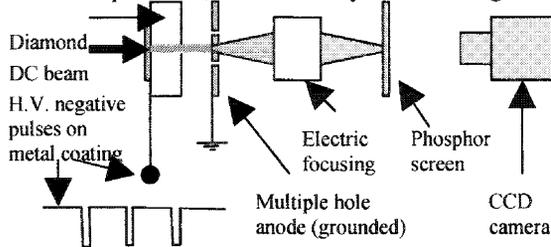


Figure 3: Diagram of emission experiment

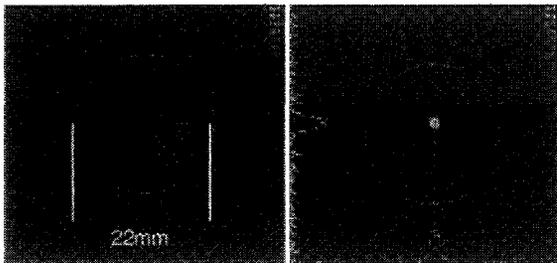


Figure 4: Left image: no focusing,  $I_{pri}=300nA$ , repetition frequency=1kHz, pulse width=10 $\mu$ s, pulse amplitude=-3kV. Right image: with focusing, reduced  $I_{pri}$ . The small bright dots on the right image are the images of the multiple holes on the anode

The 4x4x0.3mm single-crystal synthetic diamond was chemically etched before one surface was hydrogenated. Afterwards, the opposite surface was coated with 15nm of Ti, followed by 25nm of Pt. We then assembled the sample on the sample holder in such a way that there was a gap of about 270 $\mu$ m between the H-surface and the anode. The anode has seven small holes, 200 $\mu$ m in diameter, uniformly distributed on a 1mm<sup>2</sup> area at its center. The anode is grounded. A 10keV DC electron

beam with spot size of about 0.5mm<sup>2</sup> strikes the diamond on its metal coating side. The primary beam current ranges from 100nA to 2 $\mu$ A. At this point, we applied high-voltage negative pulses on to the diamond's metal coating, using a special high-voltage push-pull circuit that allowed us to accurately control the amplitude of the high voltage, the pulse's width, and the duty cycle. The left image of Fig. 4 is the first phosphor-screen image of the electrons emitted from the diamond amplified cathode, without electric focusing. The right is one with electric focusing but reduced current density.

### DISCUSSION

In this emission-mode test, we used a pulsing technique that can be described as follows: There is no field within the diamond before the high voltage pulse. When the voltage is pulsed "on", a field builds up immediately in the diamond and since the primary current is already on, emission of secondary electrons starts. Meanwhile, the field in the diamond starts decreasing due to the two following mechanisms:

- The increasing shielding of the applied field, as discussed.
- Trapping of secondary electrons near the H-surface during their emission.

Figure 5 depicts a possible mechanism of electron trapping near the H-surface.

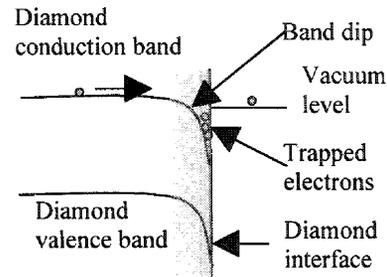


Figure 5: Schematic of electron trapping near the emission surface

As fig.5 shows, although the vacuum level is lower than the minimum of the conduction band in the bulk of the hydrogenated diamond, the small band bending near the H-surface generates thin layer near the surface where the vacuum level is higher than the conduction band's minimum. Those secondary electrons that do not undergo inelastic collisions in that range, and those with the final energy higher than vacuum level even with collision, will emerge from the diamond. On the other hand, if the electrons lose too much energy in that range they can be "trapped". These trapped electrons also shield the external field. If the current density is high, electron trapping will quickly halt the emission. Unlike the first mechanism, this shield strongly depends on the primary electron density.

Shielding of the external field is a relatively slow process. As shown in fig.2, for 0.3MV/m of external field at room temperature, the gain at beginning of the beam's pulse drops to 90% of its peak gain in milliseconds of  $T_{Delay}$ . Higher external field, lower temperature or shorter

$T_{\text{Delay}}$  can reduce the relative shielding. For example in conditions in fig.2, if  $T_{\text{Delay}}$  is less than  $100\mu\text{s}$ , this effect can be ignored.

Secondary electron trapping on the H-surface is a fast process, taking place immediately when secondary electrons arrive the H-surface, about 1ns in our test. When the applied field is high enough, the pulse width is short enough, or the current density is low enough, the field within diamond can be considered constant during the emissions. After removing the applied field, these trapped electrons either move back to the diamond's metal-coated side, or the holes move to the H-surface to recombine due to their self-induced field; then, the diamond returns to its original state.

Now, we must answer the following key questions:

- What is the probability of secondary electron trapping on the H-surface?
- What is the gain, the current density limit, and the bunch-charge limit of the beam?
- What is the lifetime of the diamond-amplified cathode?

To measure the trapping probability, first we must control accurately the voltage amplitude, pulse width, and repetition frequency, and then measure the primary electron current. An integration circuit will record the average emission current. Calculating the emission gain when the duty cycle is known is straightforward.

Having determined the emission gain, we can compare it to the gain data from the transmission-mode measurements [2] to find the trapping probability.

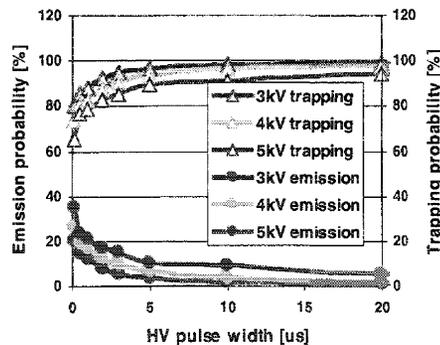


Figure 6: Emission and trapping probabilities of the secondary electrons on a hydrogenated diamond surface. 3kV, 4kV, and 5kV correspond, respectively, to a 1.7MV/m, 2.2MV/m, and 2.7MV/m field in the diamond.

Fig. 6 shows the emission and trapping probability data (emission + trapping = 100%) as a function of the width of the high-voltage pulse for one of our samples. Clearly, the emission probability rises as width of the high-voltage pulse declines. This relationship indicates that the emission mostly is concentrated in a short time at the beginning of the pulse. The highest emission-probability in our experiment is about 1/3, and peak gain was about 40 at high-voltage pulse width of 200ns under a field of 2.7MV/m.

The measured bunch-charge limit was about  $50\text{pC}/0.5\text{mm}^2/\text{bunch}$  of integrated bunch charge in our emission test.

An answer to the question about the limit on current density must wait until we can test the device in an RF cavity. We measured a limit of more than  $20\mu\text{A}/\text{mm}^2$  emission current under our current experimental conditions. In a transmission-mode measurement with an X-ray beam, we demonstrated an average current of 40 mA through a 1.6 mm diameter spot ( $20\text{mA}/\text{mm}^2$ ). The 1 ns durations X-ray bunches were generated by the NSLS, and resulted in a response from the diamond with a sub-ns rise and a 5 ns fall, consistent with the expected mobility of electrons and holes. The peak current in this case was greater than 80 mA.

The diamond-amplified cathode proved to be extremely robust. We exposed one sample to the air for a week and we did not see any degradation in its emission ability. Later, we exposed it to air for six months, and its emission ability dropped only by about 50%! This long lifetime may reflect the strong, stable chemical bonds between the hydrogen atoms and the carbon atoms.

## FUTURE PLANS

We plan to explore the emission properties, the hydrogenation effects, and the like, in greater detail. Shortly, we will measure the emittance of the emission beam. We also expect to undertake a room-temperature RF cavity test, and possibly the other termination experiments. Eventually, the diamond-amplified cathode will be tested in a superconducting cavity test stand

## CONCLUSIONS

We observed, for the first time, the phosphor-screen image of the electron beam emitted from a diamond-amplified cathode. The mechanism of DC field shielding explains the failure of our previous emission measurements. We also proposed a mechanism for electron trapping on an H-surface. Following this model, we measured the trapping probability as about 70% in one of our samples. The maximum bunch charge in our measurements is about  $50\text{pC}$  on an area of about  $0.5\text{mm}^2$ . The maximum emission gain in our present conditions is  $\sim 40$ . Another important feature of the diamond-amplified cathode is its extremely robustness; after exposure to air for days there was little degradation in its emission.

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