

## PROGRESS ON DIAMOND AMPLIFIED PHOTO-CATHODE

Erdong Wang<sup>#</sup>, Peking University, Beijing 100081, China  
 Xiangyun Chang, Ilan Ben-Zvi, Jörg Kewisch, Triveni Rao, John Smedley, and Qiong Wu,  
 Brookhaven National Laboratory, Upton, NY 11973, USA  
 Tianmu Xin, and Erik Muller, Physics and Astronomy Department, Stony Brook University,  
 Stony Brook, NY 11974, USA

### Abstract

Two years ago, we obtained an emission gain of 40 from the Diamond Amplifier Cathode (DAC) in our test system. In our current systematic study of hydrogenation, the highest gain we registered in emission scanning was 178. We proved that our treatments for improving the diamond amplifiers are reproducible. Upcoming tests planned include testing DAC in a RF cavity. Already, we have designed a system for these tests using our 112 MHz superconducting cavity, wherein we will measure DAC parameters, such as the limit, if any, on emission current density, the bunch charge, and the bunch length.

### INTRODUCTION

The diamond-amplified photocathode, that promises to support a high average current, low emittance, and a highly stable electron beam with a long lifetime, is under development for an electron source. The diamond, functioning as a secondary emitter amplifies the primary current, with a few KeV energy, that comes from the traditional cathode.

Earlier, our group recorded a maximum gain of 40 in the secondary electron emission from a diamond amplifier[1]. In this article, we detail our optimization of the hydrogenation process for a diamond amplifier that resulted in a stable emission gain of 140. We proved that these characteristics are reproducible. We now are designing a system to test the diamond amplifier cathode using an 112MHz SRF gun to measure the limits of the emission current's density, and on the bunch charge and bunch length.

### HYDROGENATION EXPERIMENTS

The hydrogenation experiments were carried out in a bakeable UHV chamber evacuated to  $1.3 \times 10^{-9}$  torr by a turbo pump and an ion pump. The chamber was equipped with a residual gas analyzer and a hydrogen cracker. We placed the diamond, biased to -50V, on a button heater and heated it to 800°C. The temperature was monitored with a thermocouple, placed in thermal contact with the sample's base. We illuminated the diamond directly with a deuterium lamp that has a continuous emission spectrum between 190- to 300-nm. The lamp was coupled to a UV monochromator, enabling us to obtain the

spectral dependence of photoemission in this spectral range. The diameter of the UV light's spot was 3 mm, covering nearly the entire hydrogenated surface of the diamond. To fabricate the diamond amplifiers, we coated one side of a high purity  $4 \times 4 \text{ mm}^2$ , 300um-thick single-crystal diamond samples, grown by chemical deposition (CVD) with Pt; the opposite side was hydrogenated. The steps in fabricating diamond amplifiers were as follows,

The diamond sample was cleaned ultrasonically in acetone, then in alcohol for 15 minutes and dried by the pure nitrogen.

- We sputtered 35nm Pt on one side of the diamond wafer.
- We heated the sample to 800°C to clean its surface.
- We shone UV light on the hydrogenated surface to measure the photo current.
- We turned off the heat
- We exposed the sample to a flow of hydrogen atoms generated by a MANTIS MGC75 thermal gas cracker, both while the sample was cooling and while the sample has reached room temperature.

The quantum efficiency of its photoemission is one important parameter of the hydrogenated diamond. The threshold wavelength is an indicator of the formation of negative affinity of surface.

We compared four diamonds hydrogenated at room temperature and four at high temperatures. For the latter high temperature hydrogenation, after the diamond's temperature reached 800 °C, the heater was turned off and hydrogenation was started, continuing as the sample's temperature decreased gradually to 320°C. For room-temperature hydrogenation, we let the sample cool down to 23°C before starting hydrogenation. For both processes, we set the power of the hydrogen cracker at 50W with the hydrogen partial pressure at  $10^{-6}$  torr. The electron yield was monitored while a 220 nm, 2.25uW UV ray was shone on the diamond.

Figure 1 shows a typical curve for photocurrent yield from the hydrogenated surface of sample treated at 800°C (red curve), and at 23°C (black curve). As shown in Figure 1, the photo-current took 30 minutes to reach its peak; in contrast, when the diamond was hydrogenated at 23°C, the photocurrent attained a peak in 10 minutes. The speed of hydrogen deposition differs at these two different temperatures. At high temperature, hydrogen could attach to the carbon atoms, and detaches from them. Hence, it takes a long time to attain optimum coverage. In contrast, at room temperature, the hydrogen detachment could be insignificant, so that optimum

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<sup>#</sup>wedwrd@gmail.com

coverage is reached in a short time. Extending the duration of hydrogenation does not increase the coverage. Rather, it exposes the sample for longer duration to contaminants that are released from the cracker, and may entail impurities impinging on the diamond's NEA surface, and causing the decay of the photo current. Such reduction could not be recovered by subsequent re-baking or re-hydrogenating the sample. After hydrogenation (after the cracker was turned off and hydrogen pumped from the system), we measured the change in QE over time with a 220 nm beam. In 11 hours, the QE of the diamond processed at high temperature dropped 13%, while that of the diamond treated at room temperature declined 50%. Thus, the NEA surface produced in high-temperature hydrogenation is more stable than the one created at room temperature.

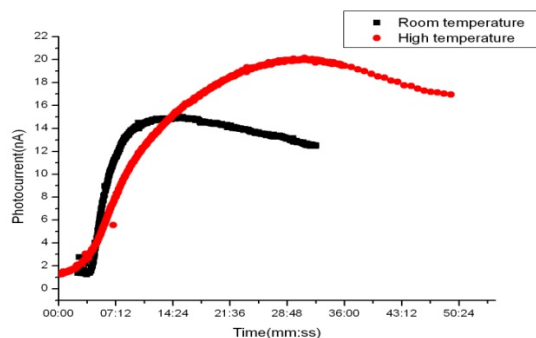


Figure 1: The trend in photocurrent yield in the hydrogenation process. Red curve is high temperature hydrogenation, and, black curve is that at room temperature.

The diamond amplifier is extremely robust, and is stable during exposure to air. The water vapor in the air inhibits electron emission from the amplifier<sup>2</sup>. Heating diamonds exposed to the atmosphere removes water molecules from their surfaces. We explored the optimal temperature for such evaporation. The photocurrent of a diamond amplifier with a newly formed hydrogenation surface was 17nA; exposing it to air for 1 hour caused the emission current to drop to 2nA. We then heated the diamond to 200<sup>o</sup> C for 30 minutes and cooled it down. Our measurement of the photocurrent demonstrated the recovery of the diamond's photocurrent to 10nA. We scanned the photo-current as a function of the temperature of baking: Figure 2 plots this data, showing that the optimized temperature is 450<sup>o</sup>C, at which the photocurrent recovered to 96% compared to that of a amplifier unexposed to the atmosphere. The results prove that the quality of hydrogenation is recovered by baking. However, baking at temperatures higher than 450<sup>o</sup>C breaks the hydrogen- and carbon-bonds, while at 800<sup>o</sup>C, hydrogen atoms are removed from the diamond surface leaving it bare.

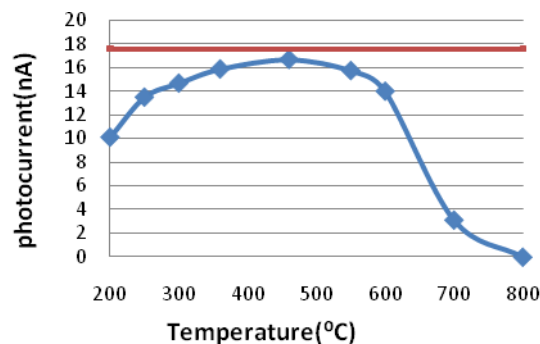


Figure 2: Temperature scanning for optimizing the baking of the diamond. The red line is the photocurrent of a freshly hydrogenated diamond. The blue curve is the photocurrent following 1 hour exposure to air and after heating to the given temperature and cooling down the sample.

## GAIN MEASUREMENT

Our set-up for measuring the emission-mode gain consists of a thermionic gun, a high-voltage pulse supply, an anode, and a phosphor screen; details on the experimental arrangements are published elsewhere<sup>3</sup>. The thermionic gun supplies the DC primary electrons that penetrate the metal layer. There is a gap of 200- to 500-um between the anode and the diamond's hydrogenated surface. The high-voltage, applied between the anode and the metalized surface of the diamond, generates a field in the diamond and across the gap towards which electrons emitted from the diamond are accelerated. The average value of the emission current is measured by the integrated anode current. The anode is grounded through the electrometer. The emission gain is defined as the ratio of the collected current on the anode to the primary electron current.

The hydrogenation chamber and emission-mode gain test chamber are separate. Transferring the freshly hydrogenated sample from the hydrogenation chamber to the test chamber exposes it to the ambient air for 30 minutes, during which the surface absorbs water molecules. Our gain measurements showed that the highest gain of the diamond amplifier is 128 following a 350<sup>o</sup>C heating- and cooling-cycle. We then exposed the amplifier to dry N<sub>2</sub> or to air at 1 atm for 30 minutes; we registered a gain of 124 after exposing it to N<sub>2</sub>, and 119 after exposure to air.

Next, a freshly hydrogenated diamond amplifier, only briefly exposed to the air, was installed in the test chamber. We heated it to 200<sup>o</sup>C under an ultrahigh vacuum ( $\sim 10^{-10}$  torr), held it at this temperature for 40 minutes, and then left it to cool to room temperature. The gain at the centre of the amplifier was 95. Heating it thereafter for 40 minutes at 350<sup>o</sup>C (the limit in our test chamber) realized a gain of 135 at the same location on cooling. This result reveals that the optimum temperature for heat treatment is much higher than 200<sup>o</sup>C.

These findings gave us the optimum parameters for hydrogenation and baking, resulting in diamond samples with reproducible NEA surfaces, high QE, and gain. We fabricated five more samples, and the gain in all of them stably reached more than 100. Diamond amplifiers are drift-dominated cathodes, so the diameter of secondary electron beam reaching the emission surface is nearly the same as that of the primary bunch. We used it to scan the diamond amplifier. The primary electron-beam's size was minimized to  $0.5 \text{ mm}^2$ ; Figure 3 shows findings from the secondary emission scan. The highest emission gain we measured was 178. Figure 4 shows the gain in each of the five amplifiers we fabricated. The different gains at different locations within the whole piece could reflect some non-uniformities of the bulk, hydrogenation surface and the metal coating.

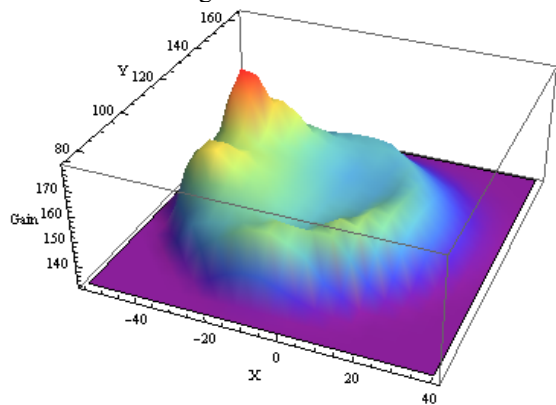


Figure 3: Scan of the diamond amplifier's secondary emission. The vertical axis Z is the gain number. X and Y are the coordinates of the position.

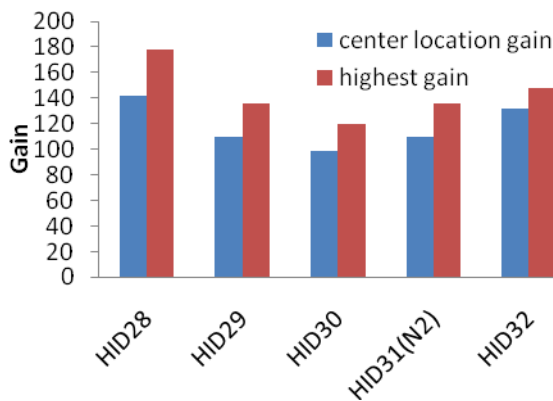


Figure 4: The gain in five different diamond amplifiers. HID 31 was protected in dry  $\text{N}_2$  during its transfer from the hydrogenation system to the gain test system. The blue columns give the gain at the centre of the diamond amplifiers, and the red columns show the maximum gain of the samples.

### RF GUN TEST

The RF gun that will be used in the experimental tests of the diamond amplifier is a 112MHz superconductive electron gun manufactured by Niowave and BNL[4].

The diamond will be mounted on a 1.35-meter long stalk as shown in figure 5. The UV laser will emerge from the back of the stalk and be reflected by a dielectric coated mirror on to the photocathode. The reflected laser from the cathode's surface will strike another symmetrically installed mirror and be guided out of the cavity, so minimizing the effect of multi-reflections. The designed energy of the primary electron bunch is 10KeV. A specially designed focusing tube also acts as a deflector that can adjust the transverse position of the primary electron spot on diamond in a range of 3 mm. If the RF phase is correctly chosen, the secondary electrons will be accelerated by the RF field towards the diamond's cavity side and eventually will be emitted from hydrogenated surface of diamond amplifier. We anticipate this secondary electron beam. The current will be more than 100 times higher than that of the primary one.

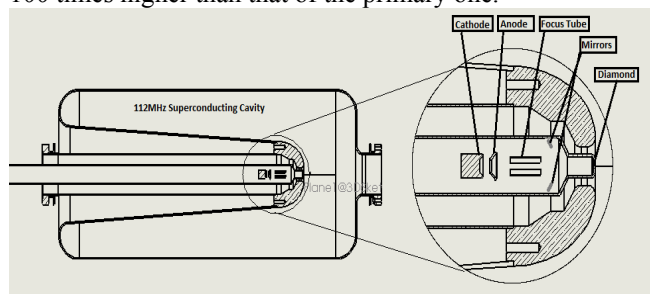


Figure 5: Schematic of the experimental arrangement for testing the diamond amplifier in the RF cavity

Once the instrument is fully functioning, we propose to study the dependence of the emission properties and the temporal profile of the secondary electron bunch as well as the limitations on the charge, current and current density.

### CONCLUSION

In this work we studied the effect of hydrogenation on the NEA surface of diamond amplifiers. We found that high-temperature hydrogenation yields a higher quality NEA surface compared to the hydrogenation at room temperature. Hydrogenated diamond amplifiers are less affected by exposure to the atmosphere. We optimized the bake temperature to recover the maximum electron yield in both the hydrogenation chamber and in the test chamber. Our treatments result in the improved and reproducible performance of diamond amplifiers. Addition, the 112MHz RF gun test for diamond amplifier is carrying on.

### REFERENCES

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