Secondary-electron emission from hydrogen-terminated diamond

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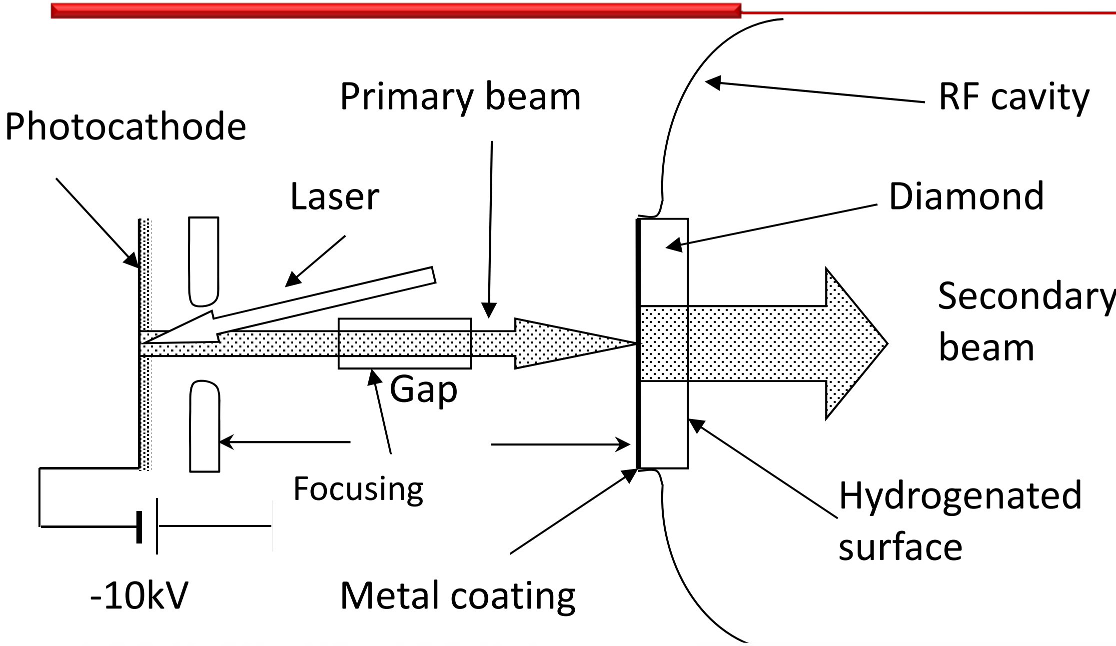
- Motivation
  - -High average current electron source requirement
  - -Diamond amplifier concept
- Experiments
  - -Hydrogenation optimization
  - -High gain emission test
  - -Lifetime and uniformity
- Emission models development
  - -Effective NEA surface
  - -Energy Spread
  - -Emission gain depend on pulse width
- Summary

Motivation

- High average current, high-brightness, low emittance injector requirement:
  - -ERL light source
  - -E-cooling

- Desired cathode:
  - -High peak current
  - -High average current
  - -Low transverse emittance
  - -Fast temporal response
  - -Small energy spread
  - -Simple installation expose to air, no load-lock mechanism requirement
  - -Long life time
  - -Should not contaminate gun

Diamond amplifier concept



- Metal photocathode: QE 0.1% , long life time (months)
- Semiconductor photocathode: QE 1% ~ 10%, short life time (weeks)
- Diamond amplifier, high current, long lifetime

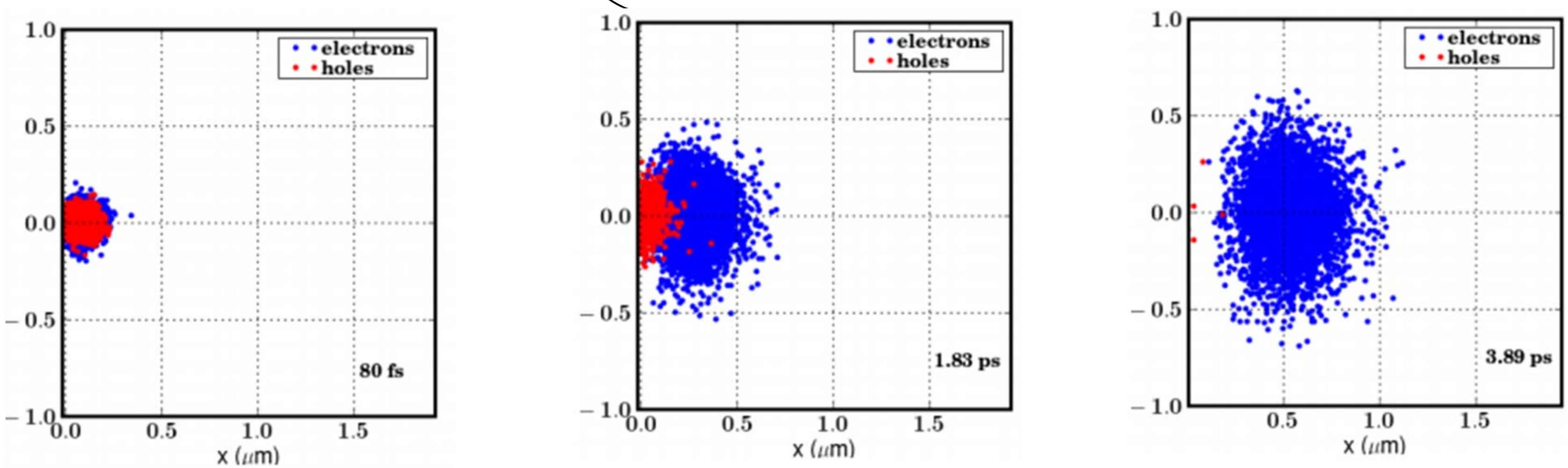
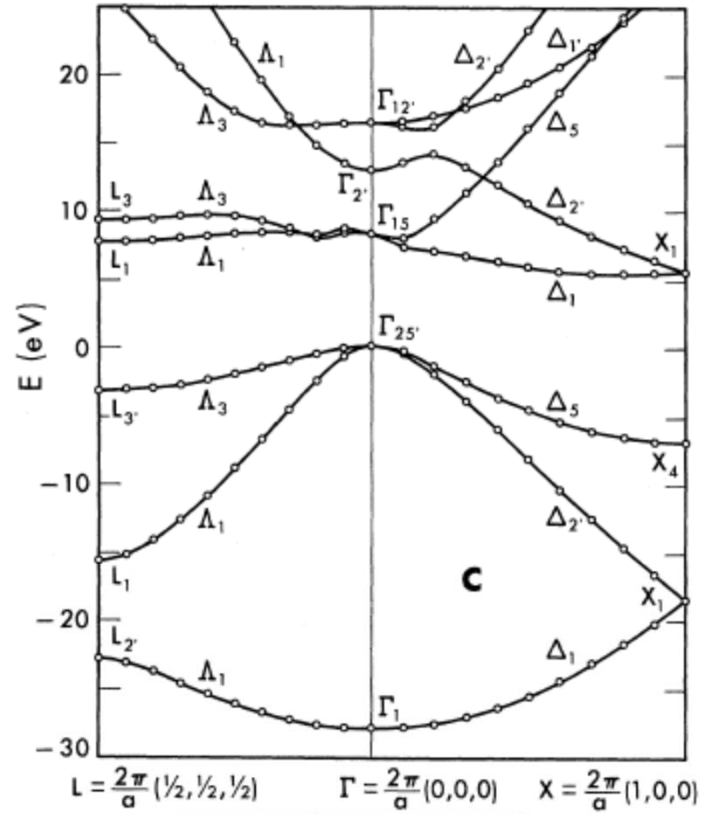
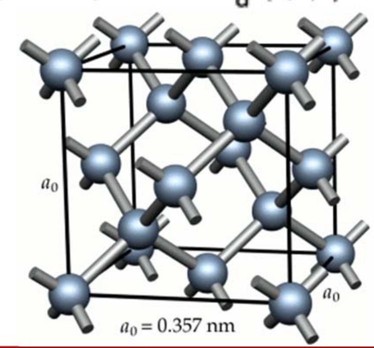


Diagram courtesy of D.A.Dimitrov (Tech-X Crop.)

Why we choose diamond?

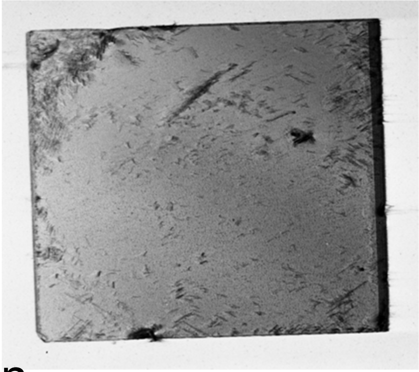
- Wide band gap
  - Diamond has a band gap of 5.47 eV; indirect band gap
  - Material with larger band gap will have the ability of tolerant stronger electric fields. Prevent field emission and dark current.
  - Could have negative electron affinity (NEA) with hydrogen termination on the surface, due to the large band gap
- Best rigidity
  - Diamond window will protect the gun from cathode material.
- High thermal conductivity
  - -- Easily handle heat power from primary current deposited
- Very high Mobility and Saturation Velocity
  - Saturation velocity is 2.7×10^5 m/s. It have high frequency application





Diamond amplifier fabrication

•Single crystal CVD diamond (Element 6); X ray topography.



(110) X ray topography

•Surface clean

The diamond sample was cleaned ultrasonically in acetone and then in alcohol for 15 minutes.

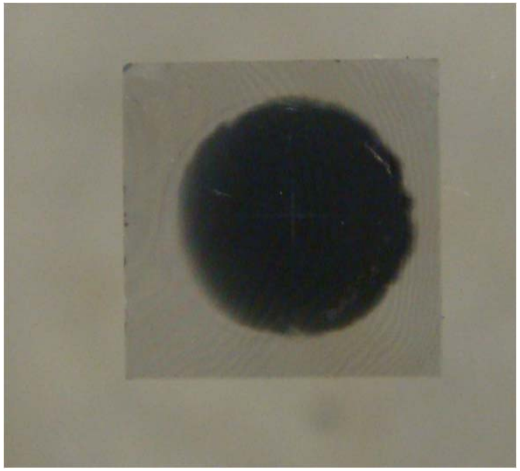
•Metal Pt Sputtering

Sputter 30nm Pt layer

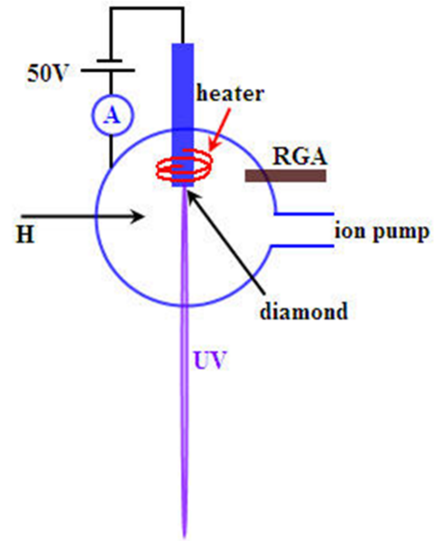
$$G = \frac{E_{primary} - E_{metal}}{E_{e-h}}$$

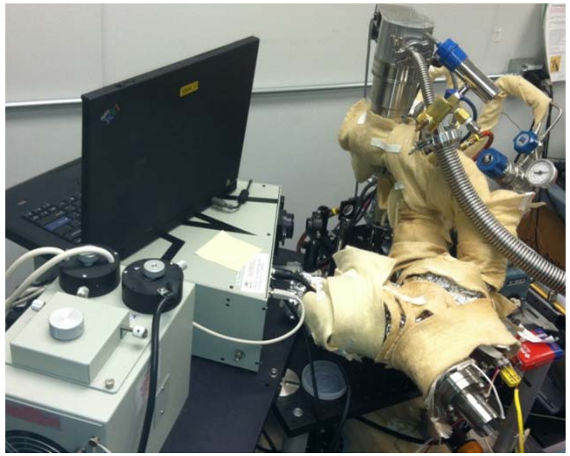
•Hydrogenation

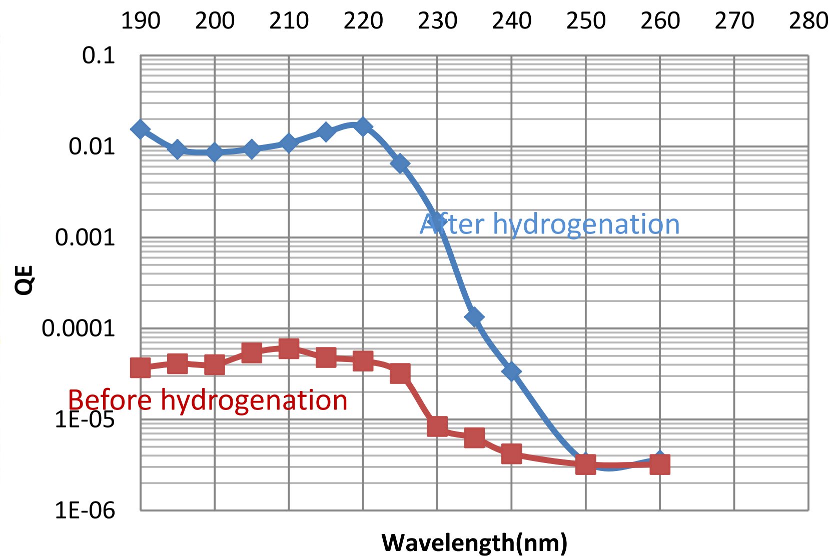
Generate NEA surface，determine the high gain of diamond



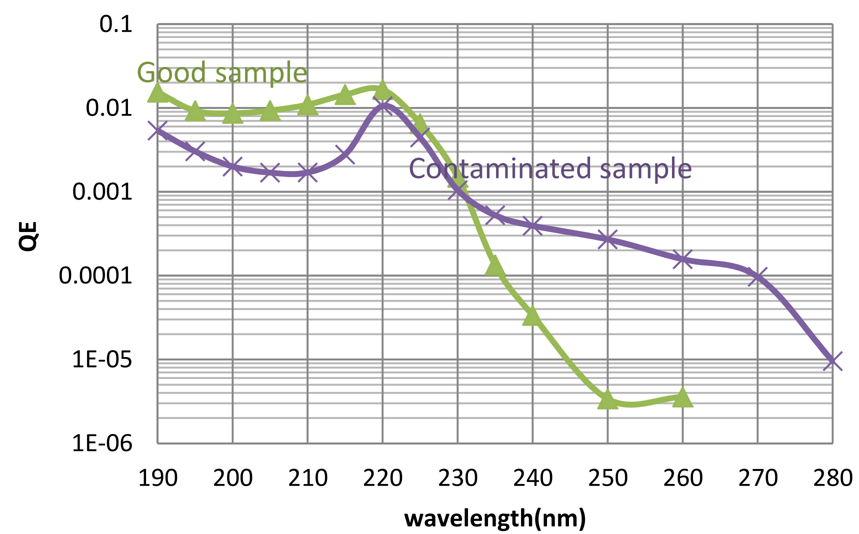
Hydrogenation



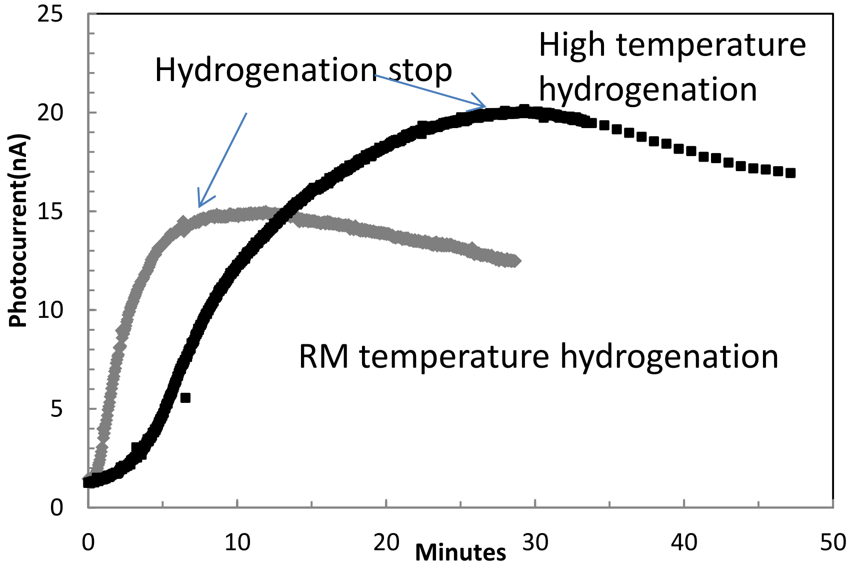


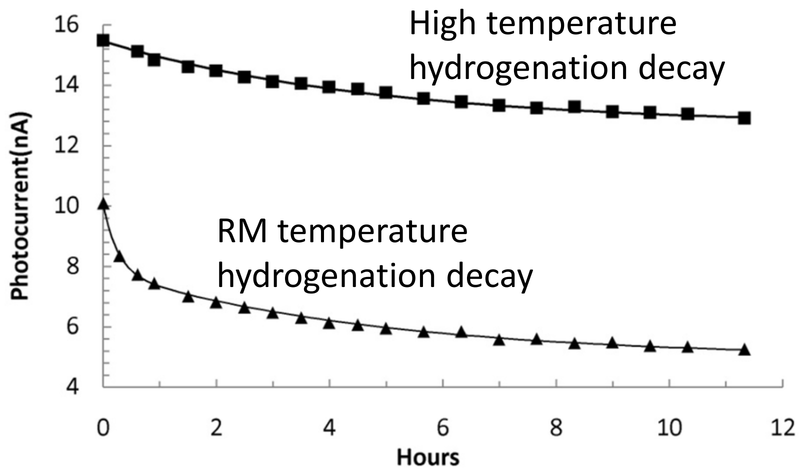


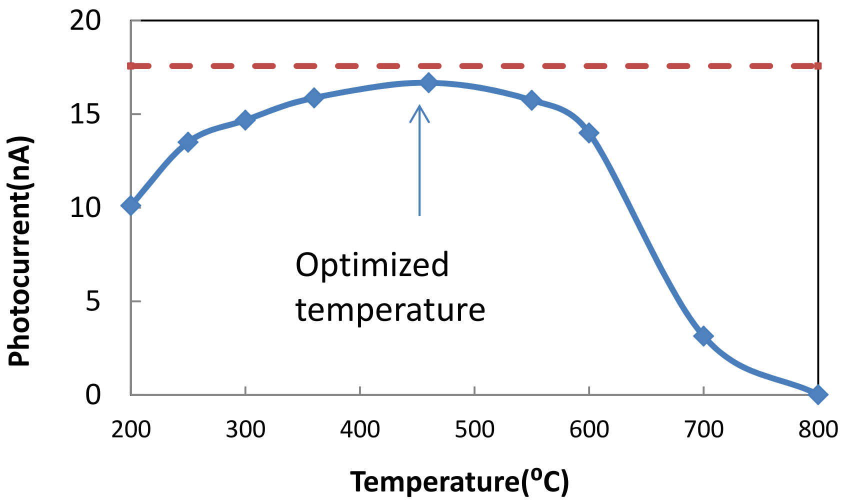
1. Heat to 800 ºC for 30 minute.
2. Cool down and measure background emission spectrum, then heat to 800 ºC.
3. Expose to hydrogen atoms with10^{-6} torr.
4. Monitor the photocurrent increase once turn off the heater.
5. After the photocurrent reached its peak, Turned off the hydrogen atoms
6. Measured the emission spectrum after sample cool down.



Hydrogenation optimization

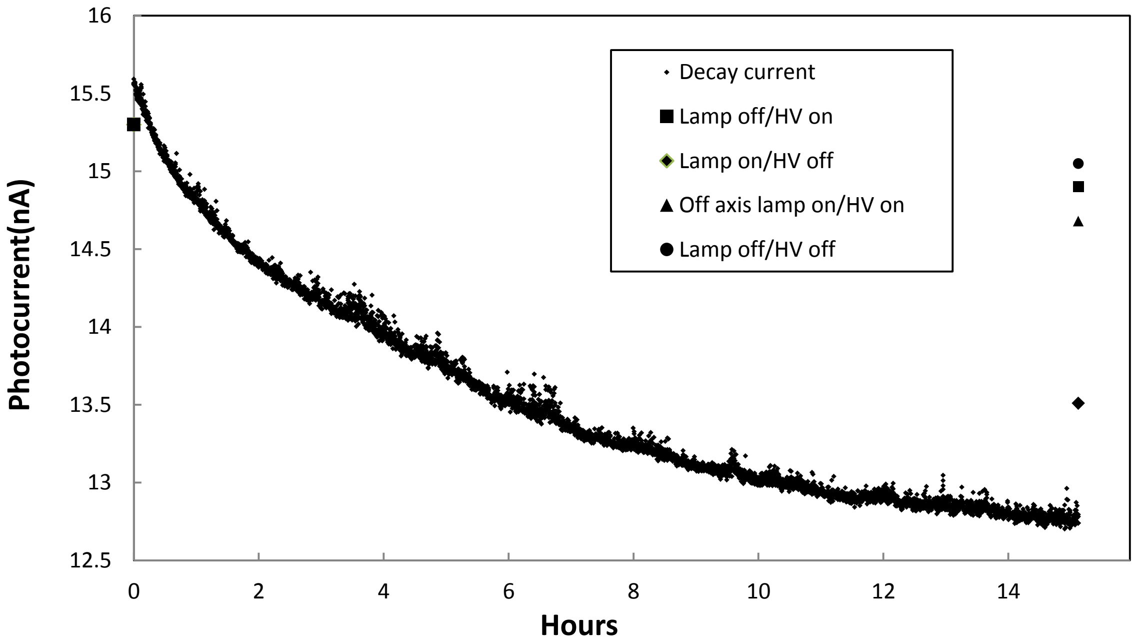






- •Slow decay after high temperature Hydrogenation (4.8 hrs)
- •Twin decay after RM temperature Hydrogenation (0.25hr， 4.8hrs)
- •Slow decay be recovered by baking ,but not in quick decay

Lifetime of diamond amplifier

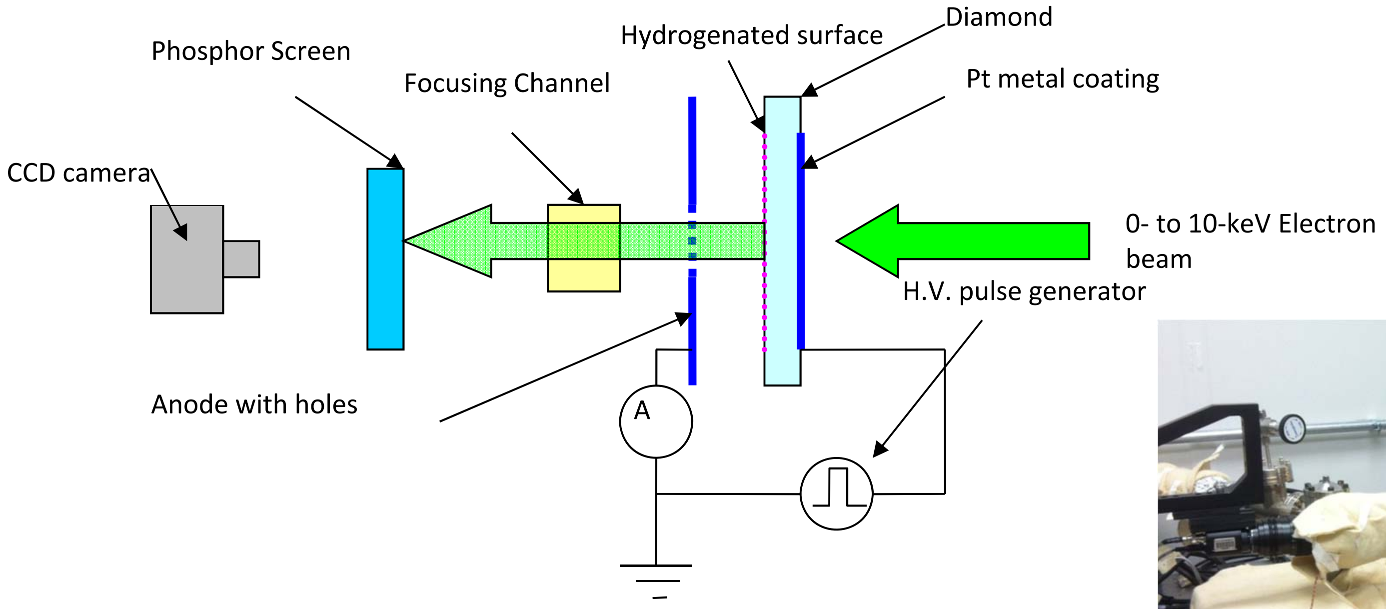


Total	18%
Residual gas	1.9%
UV light	9.8%
Bias	0.7%
Ion back bombardment(emission)	4.2%
Ion back bombardment(UV)	1.4%

- Hydrogenated diamond exposed to atmosphere for 30 minute, then gain drop 5%
- New diamond amplifier gain is 135
- One month later, gain still above 90
- Exposed to atmosphere four months, gain 130 after re-hydrogenation

Hydrogen-termination is robust!

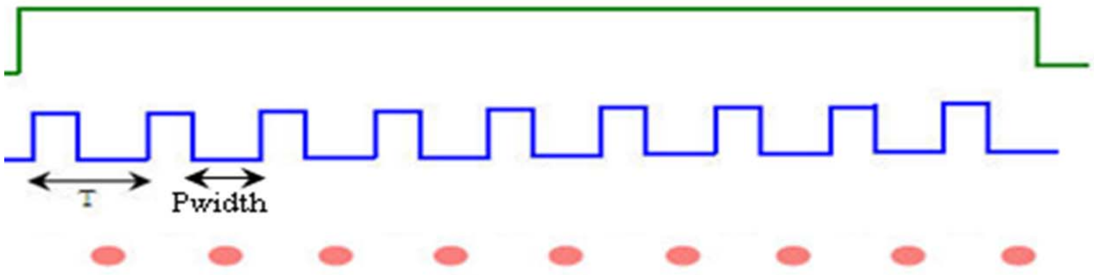
Emission gain test



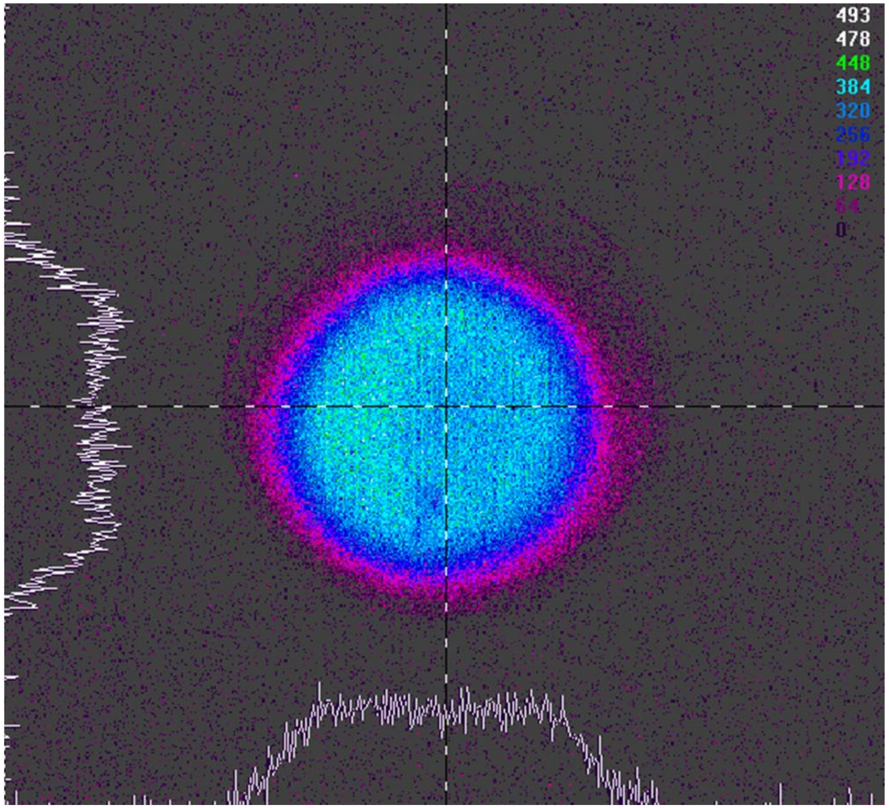
Primary current

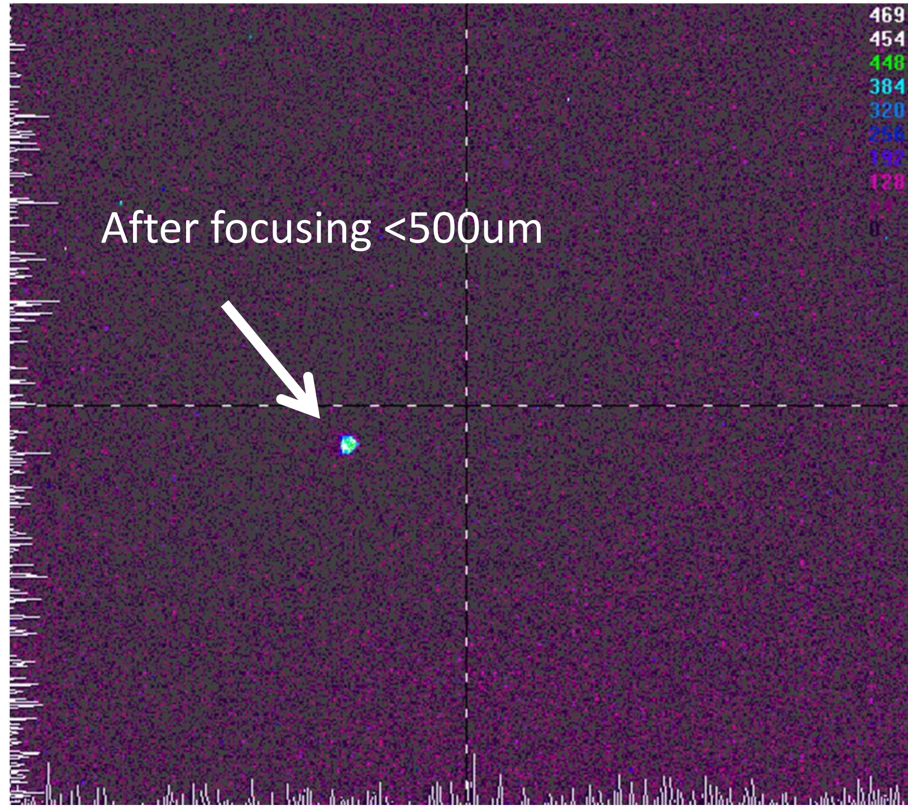
HV pulse

Secondary current



Secondary electron beam

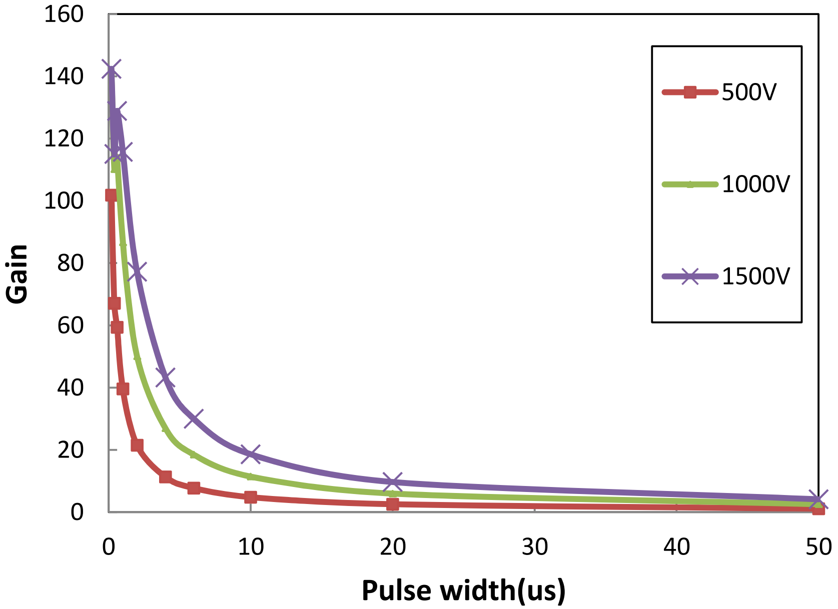


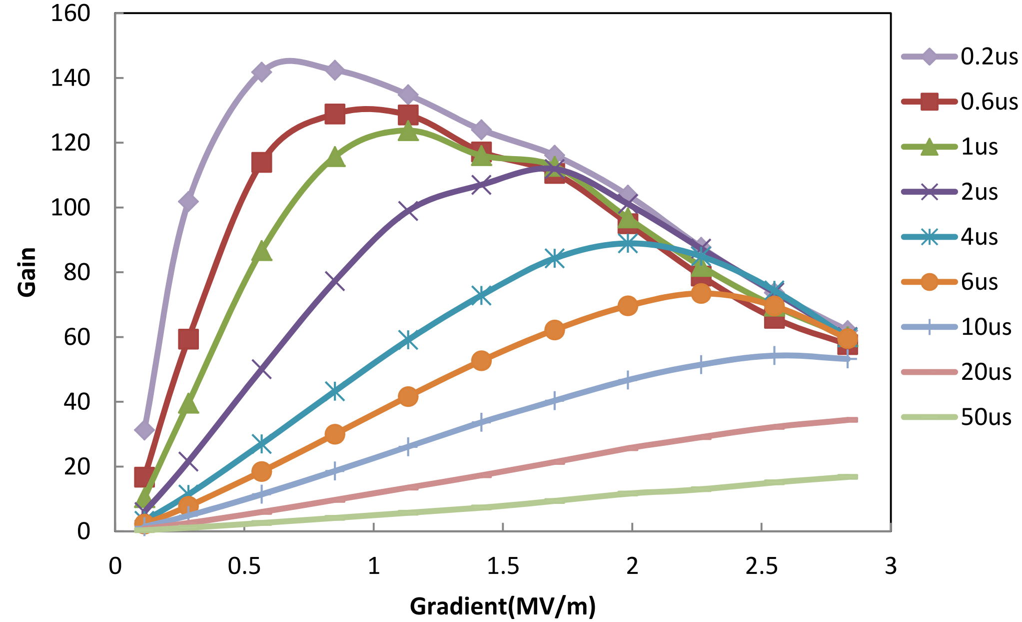


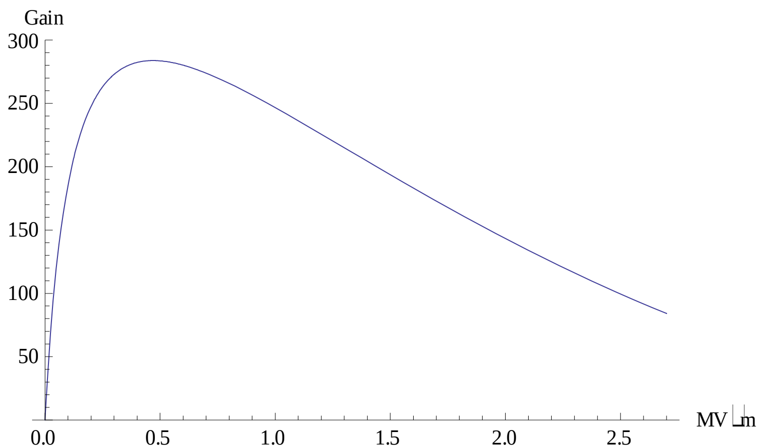
Frequency:1000Hz
Pulse voltage:3000V
Pulse width:10us
Current:169nA

The highest bunch charge: 500 pC @1 mm^2
Current density:70 $\mu A/mm^2$

Gain measurement

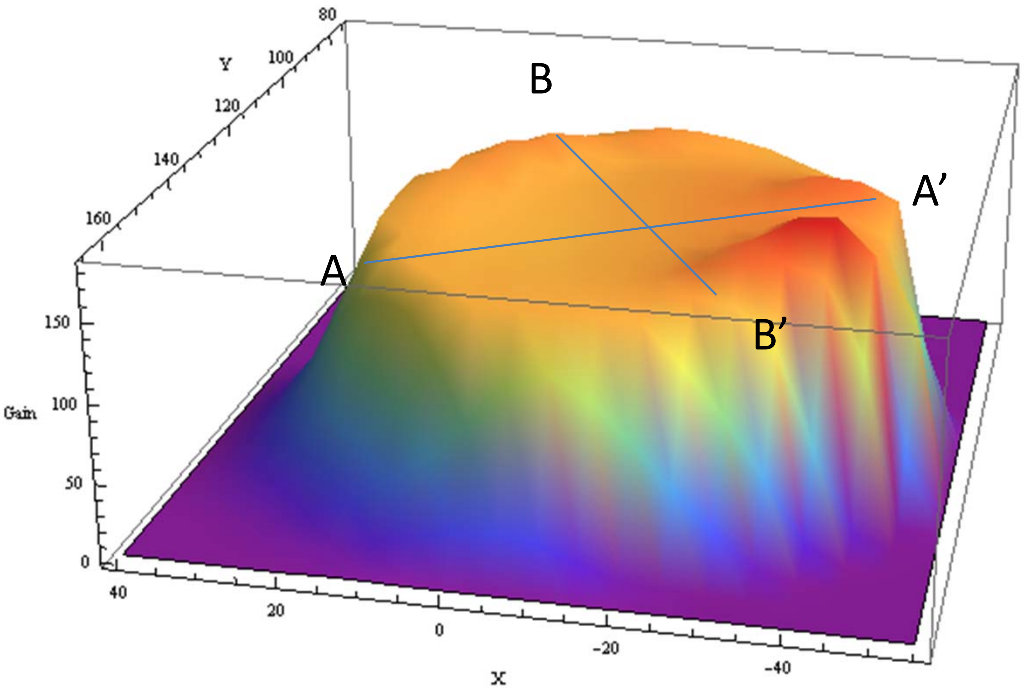




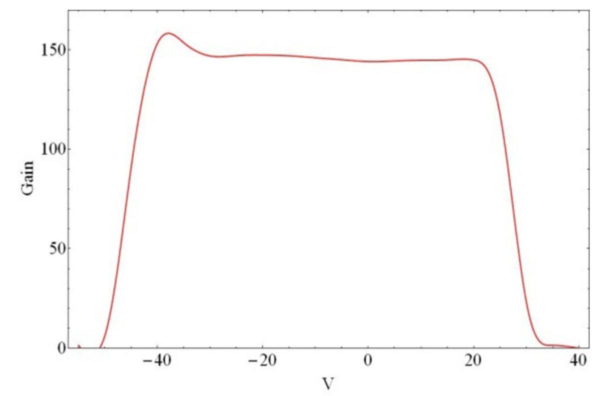


- Diamond biased to negative voltage, thermionic gun is -10 kV. Primary electrons energy drop when the voltage of diamond increase, so gain drop
- The gain drop due to trapping electron accumulate on the surface when the pulse width increase
- Without the surface trapping，ideally gain is 280

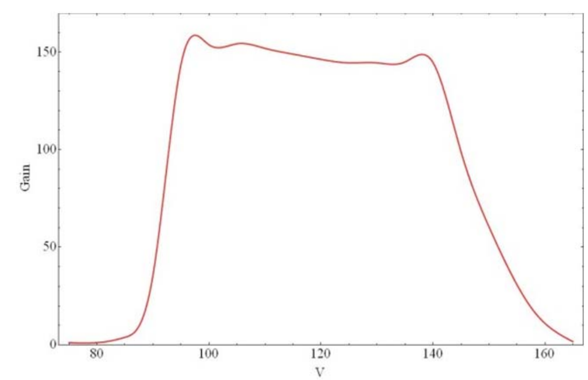
Secondary emission uniformity



A-A'

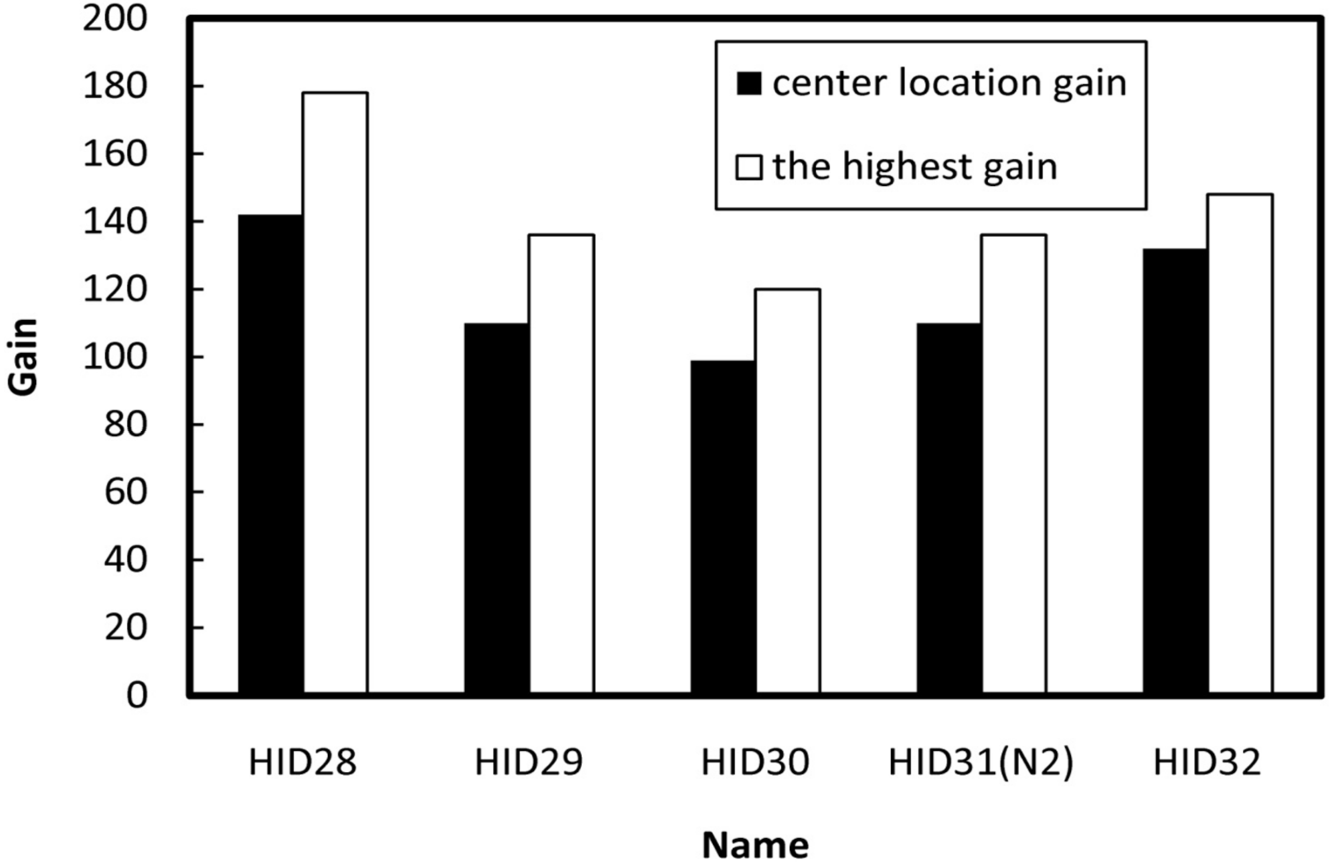


B-B'

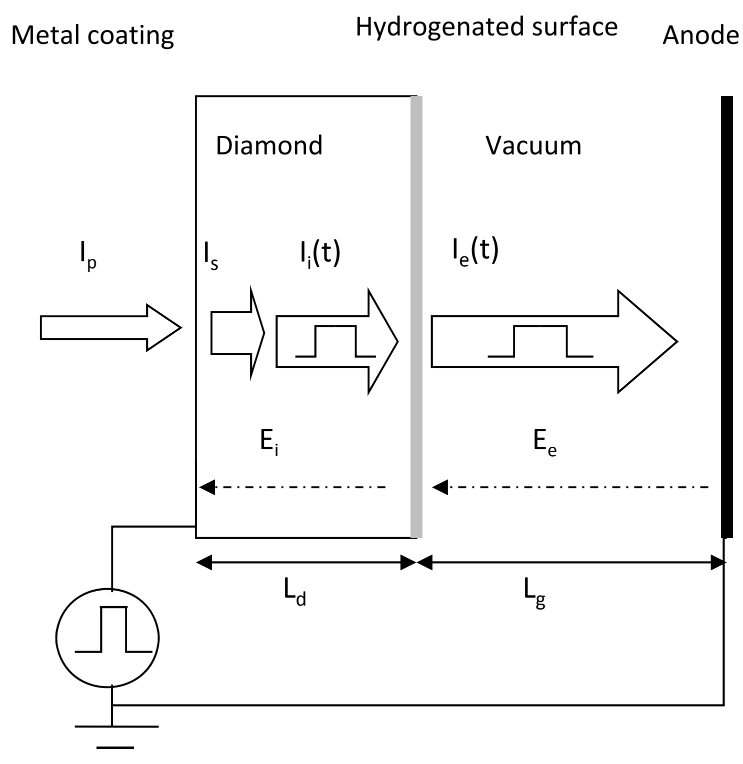


- Emission diameter 2.8 mm
- Maximum gain178
- Center gain143
- Edge gain increase due to thin metal layer

Reproducible



Emission probability



Average emission gain：

$$I_a = \frac{\int_0^w I_e(t)dt}{1/f} \Rightarrow G_e = \frac{I_a}{I_p}\frac{1}{f \cdot w}$$

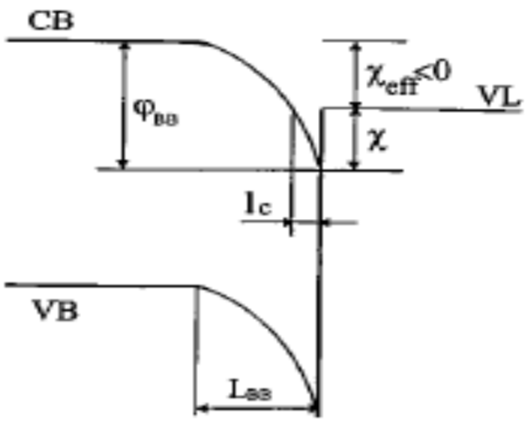
Transmission gain： $G_t = \frac{I_i}{I_p}$

Defined a parameter independent on primary beam, metal coating : Emission probability

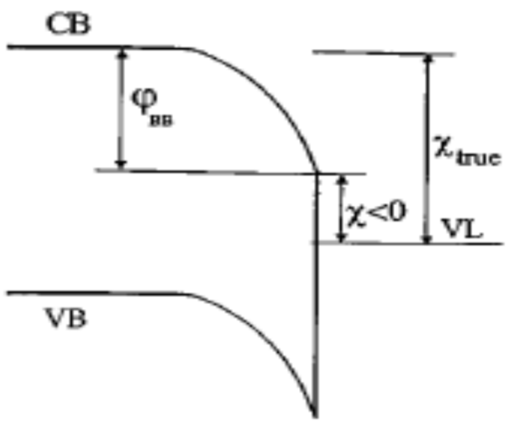
Unmeasureable : $P=I_e/I_i$
Measureable when pulse width tend to infinitely small :
$P=I_a/(I_i \cdot w \cdot f) = G_e/G_t$

Effective negative electron affinity

Effective NEA

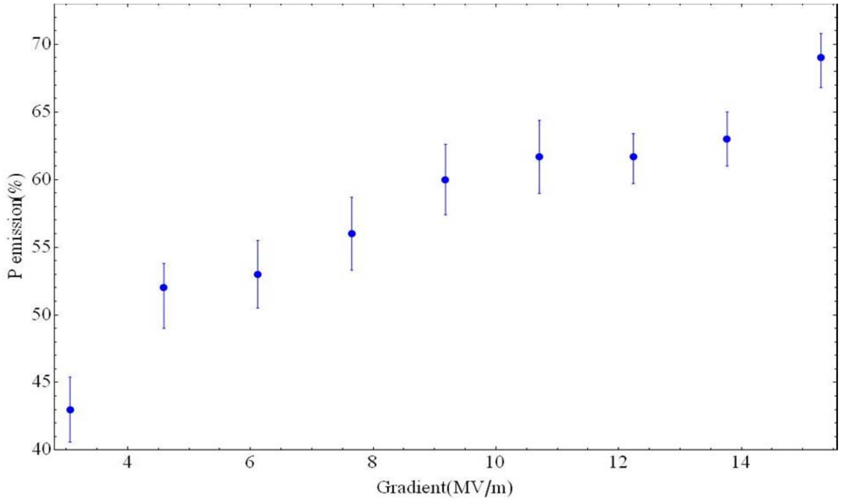


True NEA



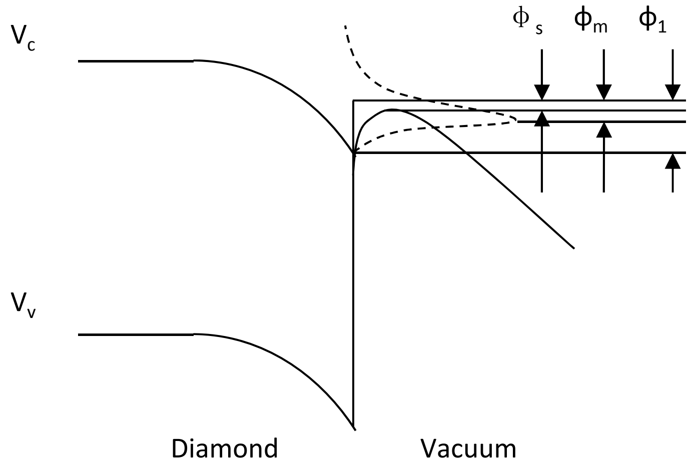
Barrier on the surface, some electrons be trapped

No barrier on the surface, totally emission



The hydrogenated diamond (100) surface is effective NEA

Schottky effect on diamond surface



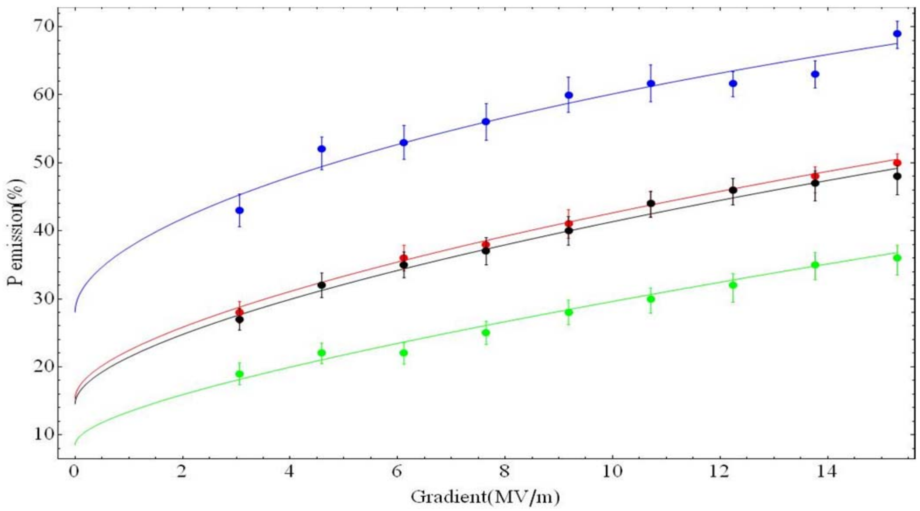
Schottky effect: $$\phi_{sch\_dia} = 0.0318\sqrt{E_0(MV/m)}[eV]$$

Distribution: $$f(x) = \frac{e^{-\frac{(\varphi-m)^2}{2\sigma^2}}}{\sqrt{2\pi\sigma^2}}$$

Gauss peak to vacuum level

Emission probability: $$P = 1 - \frac{1}{2}Erfc(\frac{\varphi_m + \varphi_s}{\sqrt{2}\sigma})$$

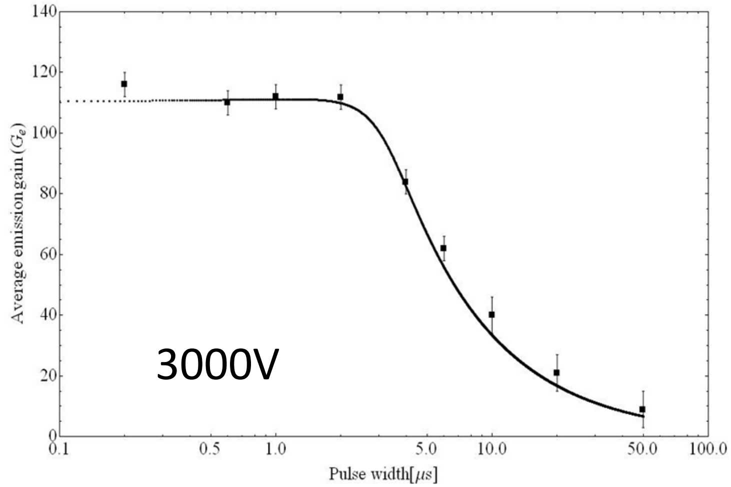
Energy spread

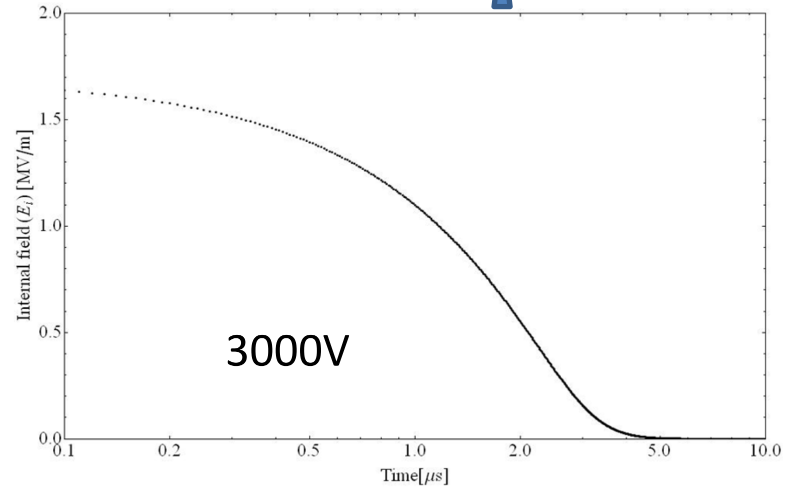


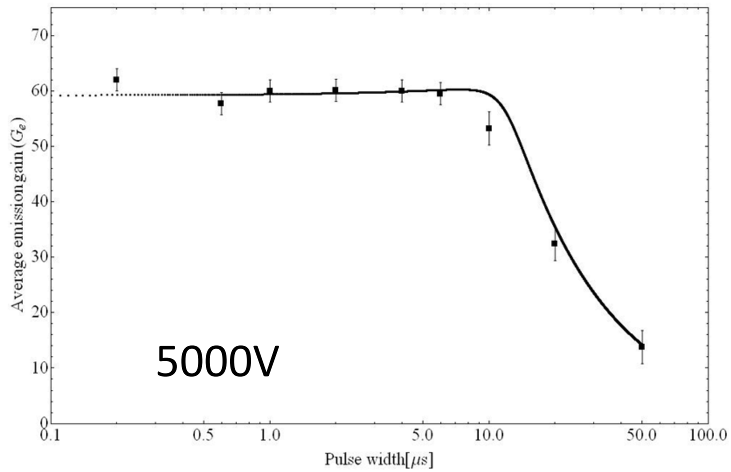
- Prepared four nearly identical samples and measured the emission probability
- Obtain σ and φ_m by data fitting
- Energy spread estimated 0.12±0.01eV

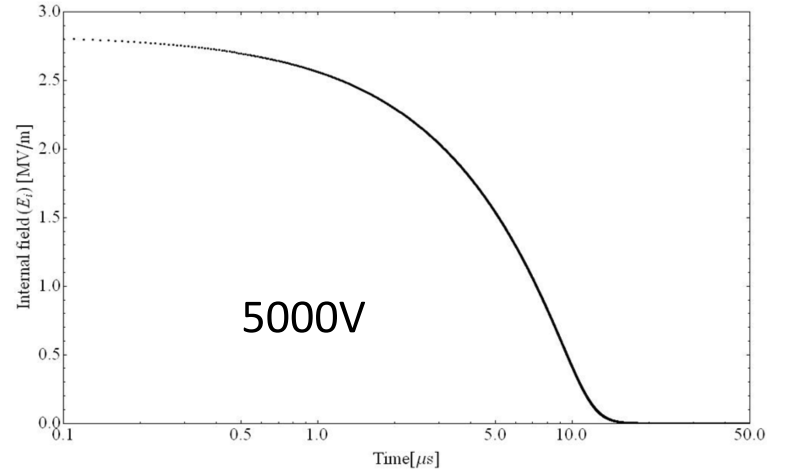
Gain depend on the pulse width

$$E_i(t) = \frac{E_e}{\varepsilon_r} - \frac{1}{\varepsilon \times S}\int_0^t (1 - P) \times I_p \times G_t(\mathcal{E}_p, E_i(t))dt$$









Summary & prospective

1. Hydrogen terminated diamond was demonstrated to amplify the electron beam from traditional cathode.
2. The standard procedure was developed after systemically hydrogenation study. The high quality diamond amplifier is reproducible now.
3. The highest measured gain was 200.
4. Developed an emission model on the effective NEA surface and the energy spread was estimated.
5. The emission gain decrease when the HV pulse width increase. This phenomena is explained well by the surface trapping model.
6. The 112MHz SRF gun for diamond amplifier test is under development.
7. Thermal emittance measurement is under going.

Acknowledgements

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