Diamond Amplifier
Status and Prospects

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Diamond Amplifier Concept

Advantages
Secondary current can be >300x primary current
  - Lower laser power
  - Higher average currents
Diamond acts as vacuum barrier
  - Protects cathode from cavity vacuum and ion bombardment
  - Protects cavity from cathode (prevents Cs migration)
  - Should improve cathode lifetime
$e^-$ thermalize to near conduction-band minimum
  - Minimize thermal emittance
Diamond Amplifier Concept

Electron saturation velocity in Diamond is ~0.2 μm/ps
Takes 150 ps to go 30 μm = 40 degrees of RF
Electrons must exit diamond in time to escape injector
Irregularity of surface will cause bunch spreading
Diamond Science at BNL

**Imaging**
- **SEM**  Scanning Electron Microscopy  Surface morphology
- **LEEM**  Low Energy Electron Microscopy  Imaging of hydrogenated surface, spatially localized LEED, work function mapping
- **AFM**  Atomic Force Microscopy  Surface morphology

**Diffraction**
- **XRD**  X-ray diffraction, time resolved  Characterization of metal contacts, including temperature of formation and crystalline texture
- **XRD**  X-ray diffraction  Diamond crystal quality; evaluation of stress caused by laser shaping

**Topography**
- **LEED**  Low Energy Electron Diffraction  Diamond crystal quality, localization and identification of defects

**Spectroscopy**
- **UPS/ARPES**  Ultraviolet Photoemission Spectroscopy  Electron affinity, energy & angular distribution of emitted electrons, lifetime of NEA surface
- **TYS**  Total Yield Spectroscopy  Evaluation of hydrogenated surface, lifetime
- **NEXAFS**  Near Edge X-ray Absorption Fine Structure  Surface elemental analysis, characterization of surface bonding, carbon formation
- **XAFS**  X-ray absorption fine structure  Titanium/diamond surface chemistry
- **EDS**  Energy Dispersive X-ray Spectroscopy  Surface elemental analysis
- **FTIR**  Fourier Transform Infrared Spectroscopy  Impurities in diamond

**Photoluminescence & Raman Spectroscopy**

**Carrier Transport and Emission**
- **Electron Generated**  Carrier Transport vs Field, Emission, Gain, Thermal Emittance
- **Soft X-ray, Monochromatic**  Charge collection distance, Charge trapping/detrapping effects
- **Hard X-ray, Monochromatic**  Measurement of mean ionization energy (gain)
- **High Flux White beam**  Current Limits, Contact requirements, Heat management
- **Micro-beam Mapping**  Localization of electrically active sites
Intercept = 3.2 keV (energy loss in contact)
Slope = 48 carriers per keV
⇒ mean ionization energy = 21 eV

Why so high?
Emission Test System

- Diamond
- DC beam
- H.V. negative pulses on metal coating
- Electric focusing
- Multiple hole anode (grounded)
- Phosphor screen
- CCD camera
Beam from diamond

Without focusing

\[ IP_{ri} = 300 \text{nA}, \ \text{HV: 3kV (1.7MV/m in diamond)}. \]
\[ \text{Freq.} = 1\text{kHz}, \ \text{Duty cycle} = 0.001 \]
Gain is roughly 25% of expected, based on transmission mode

Gain is highest at low pulse duration, suggesting surface charge trapping is causing field screening followed by loss to diffusion
Emission after 1 year in air
Why use photons?

- Penetration depth is a strong function of energy -> Can differentiate between surface and bulk effects
- Electron energy from photo-absorption is well defined – can accurately measure mean ionization energy
- Absorption edges allow differentiation of attenuation from metal vs loss of carriers to diffusion into surface
- Distinguish between electron and hole effects
- Shorter pulses and higher flux available
- Calibrated diagnostic beamlines available at NSLS
Responsivity and “Gain”

• In the detector business, the term gain is generally reserved for amplification mechanisms which add energy to the signal in the conversion mechanism (avalanche in a gas detector, for example)
• For the electron “amplifier”, this is not the case – the incident electron is losing it’s energy, and this energy is converted into carriers, much like an ionization mode gas detector (ion chamber)
• Similarly, in a photodetector, the energetic electron produced via absorption of an x-ray photon will produce many carriers
• The “responsivity” of a photodetector (in A/W) is given by:

\[ S = \frac{1}{W} e^{-\frac{t_{\text{window}}}{\lambda_{\text{window}}}} \left(1 - e^{-\frac{L_{\text{active}}}{\lambda_{\text{active}}}}\right) CE[v, F] \]

w: mean ionization energy – energy required to create an e-h pair

CE: Collection efficiency, based on Monte Carlo modeling
Responsivity vs Photon Energy

0.4 MV/m, 95% Duty Cycle for \(\text{hv}<1 \text{ keV}\), 100% for \(\text{hv}>1 \text{ keV}\)

Platinum M edge feature due to loss of photons absorbed by incident contact not field dependent

Maximum S of 0.07 A/W
\[\Rightarrow \text{w} = 13.3 \pm 0.5 \text{ eV}\]

Loss of photons through diamond reduces S for \(\text{hv} > 5 \text{ keV}\)

C K edge feature is field dependent, caused by incomplete carrier collection for carriers produced near incident electrode – electrons diffuse into incident contact and are lost

J. Keister and J. Smedley, NIM A 606, (2009), 774
Compare to electron generated carriers, for which carrier are produced within 200 nm of incident electrode – diffusion loss is likely the cause of the “high” w.
Flux Linearity and Current Limit

- X-ray focused white beam used to generate carriers
- Up to 11 W of x-ray power focused to 1.1x0.6 mm²
- Diamond absorbs ~10%
- 85 mA current
- 13 A/cm²
- Response is linear over 11 orders of magnitude
Flux Linearity and Current Limit

Power Absorbed by Diamond (W)

Diamond Current (A)

- Ion chamber Calibration
- Calorimetry Calibration
- Predicted, $W=13.3$ eV

300V DC bias (0.6 MV/m)
Pulse response, 2 MV/m
Prospects and Requirements

Gun Prospects

• Charge detrapping is necessary; simplest with pulsed (or RF) bias
  – Can be done with “off-phase” electron injection
• Required diamond thickness scales with frequency
  – 700 MHz -> 30 microns (hard, but possible)
  – Easier with lower frequency (200 MHz would be easy)
• Field in diamond of ~3 MV/m to saturate e⁻ velocity
  – Dielectric constant of 5.7 -> 17 MV/m in gun at phase of primary launch

Material and Beam Size

• High purity, synthetic single crystal material is optimum
  – Better crystals -> less trapping
  – Lower impurities -> less trapping and lower RF heat load
  – Currently limits available beam size to few mm
  – Larger crystals on the horizon
Prospects and Requirements

• Energy spread out of cathode will depend on NEA level
  – May need to engineer surface to achieve lower emittance
• Surface can be exposed to atmosphere, but requires significant bake afterward. May require bake during operation.
• Sealed “capsule” is a possibility
  – e⁻ stimulated desorption is a significant issue
  – Pumping difficult due to small dimensions
• Multi-stage amplifier seems possible
• Higher energy primaries
  – Lower loss in contact
  – Less loss to diffusion
  – Lower heat load for given current
  – More penetration depth -> More bunch spreading

• X-ray generated carriers (x-ray photocathode?)
  – ~1 keV photons
Thank you for your attention!

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