Diamond Amplifier

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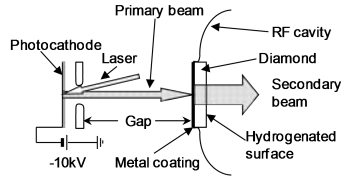
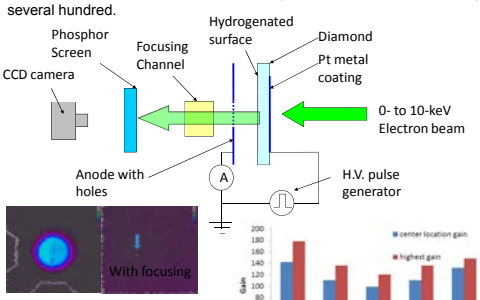
ABSTRACT

Due to its ability to form a stable negative electron affinity (NEA) surface, diamond has the ability operate as a both an electron amplifier and as a photocathode. It has the potential to dramatically increase the average current available from photoinjectors, perhaps to the ampere-class performance necessary for flux-competitive fourth-generation light sources. An emission gain of 180 has been achieved using electrons from a thermionic cathode, and transmission measurements with soft-x-ray generated carriers suggest similar "gain" is possible with energetic photons. In all cases, the electrons emitted have thermalized to the conduction band minimum prior to emission, resulting in a "thermal" spread that is independent of the incident radiation. Angle-resolved photoemission has been used to characterize this spread; the total width corresponds to the expected NEA value of -1 eV. As an indirect band-gap material, the mechanism of electron emission from the conduction band minimum requires phonon participation. Laser ARPES reveals that the NEA emission results from a novel Franck-Condon mechanism coupling electrons in the conduction band to the vacuum normal to the surface.

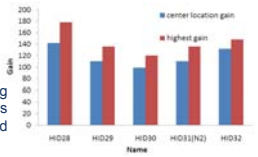
Application: Diamond Amplifier



One electron-hole pair is created in diamond for every 13.3 eV of energy deposited by incident radiation. As it is a NEA material with a long charge collection distance (typically mm for high purity single crystals), it has the potential to be an efficient, high current electron source for high energy incident radiation (electrons or photons). The electron amplifier concept combines a ~10 keV DC photoinjector with a diamond film. The primary electrons generate e-h pairs within the diamond, and these electrons drift toward the NEA surface to be emitted into an RF cavity. In this manner, the current from the primary source can be multiplied by several hundred.

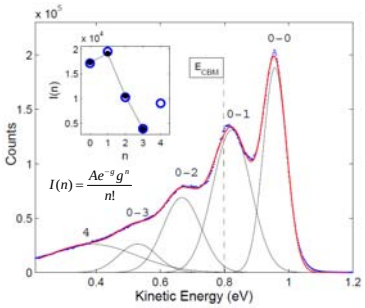


Diamond amplifier test setup, along with images of electron beams emitted from diamond with and without electrostatic focusing



Gain for 7keV primary electrons, from several diamonds

Franck-Condon Analysis of Laser ARPES



Energy Distribution Curve (EDC) integrated between ±0.02 °A^{-1}. Points (blue) show data. The line through the points (red) is the total fit.
Inset: integrated intensities of Gaussian components verses peak number n (open circles) along with FC fit (closed circles) for n = 0 to 3.

The energy distribution curve (EDC) consists of a main peak at ~1 eV and 3 satellite peaks with energy spacing of 142±5 meV. The integrated intensities of peaks 0 through 3 are fit with the Poisson distribution characteristic of phonon emission due to the Franck-Condon (FC) principle such that $I(n) \propto e^{-g}g^n/n!$ where g is the effective e-ph coupling constant, n is the peak index and I(n) is the integrated intensity of each peak. The fit yields g = 1.1 ± 0.01, in agreement with other measurements [K. Ishizaka et al., Phys. Rev. Lett. **100**, 166402 (2008)]

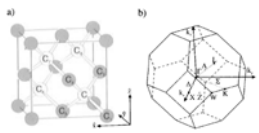
The peak energies at normal emission are: $E_k = E_{CBM} + \Sigma - n\hbar\Omega_0$

Ω_0 is the optical phonon frequency and $\Sigma = g\hbar\Omega_0$ is the real part of the electron self energy. The self energy has the effect of shifting the maximum KE of emission above E_{CBM} by $g\hbar\Omega_0$. Defining the effective NEA as the highest KE peak position we find that

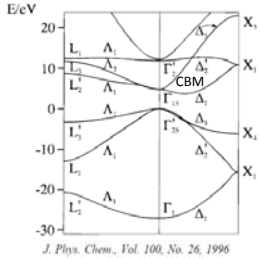
$$\chi_{eff} = E_{vac} - (E_{CBM} + \Sigma) = -0.955 \pm .005 eV$$

Why does diamond emit electrons?

Diamond has an indirect band gap, with the conduction band minimum (CBM) lying approximately three quarters of the way to the zone edge, at the Δ point. Because the CBM lies at a large absolute value of $k_{||}$ in the first Brillouin zone, very low energy emission of electrons from the sample surface, from the CBM, is kinematically forbidden. Nevertheless strong photoemission is observed, at normal emission on the [100] surface, in the absence of any zone center conduction band states. **Why?**

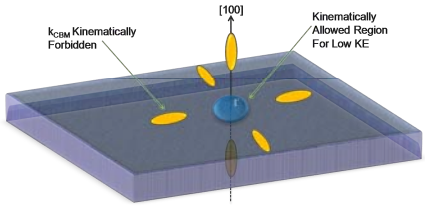


a) Diamond crystal structure (a=3.57 Å)
b) Brillouin zone



Right) Band Structure. The indirect band gap is 5.47 eV, with Δ_1=0.652 Å^{-1}. The maximum || momentum for an electron with 1 eV KE is $k_{max\,||}$~.51 Å^{-1}

Projection of k-space onto [100] Surface



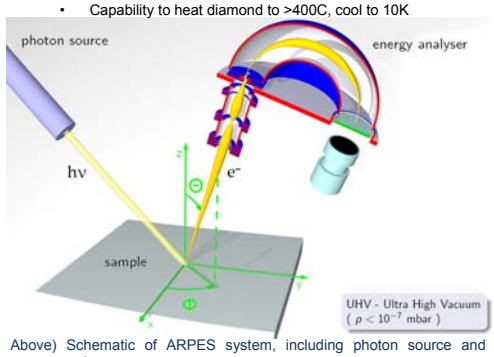
ANGLE RESOLVED PHOTOEMISSION SPECTROSCOPY ON DIAMOND

To investigate the emission mechanism and measure the intrinsic energy and momentum spread of the emitted electrons, synchrotron and laser ARPES were used. The sample used in the experiment was a device quality, single crystal type IIb diamond obtained from E6. The sample, grown by chemical vapor deposition (CVD), measured 3.5 mm^2 by 500 μm thick and was boron doped to the level of $n_B = 2\times10^{19}$ cm^{-3} (.011% B/C). The sample was hydrogen terminated using a commercial hydrogen cracker.

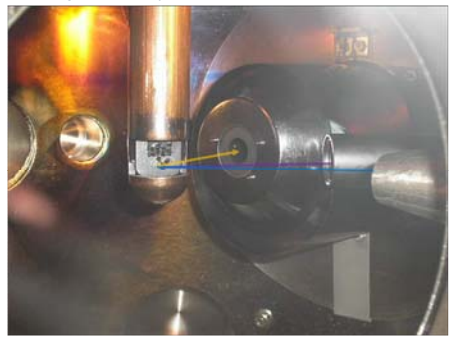
ARPES at U13

Beamline U13UB at the National Synchrotron Light Source:

- 6 eV photons from the 4th harmonic of a Ti: Sapphire laser
- 12-25 eV photons from NSLS UV ring
- Scienta SES-2002 hemispherical electron spectrometer (better than 10 meV resolution)
- Capability to heat diamond to >400C, cool to 10K

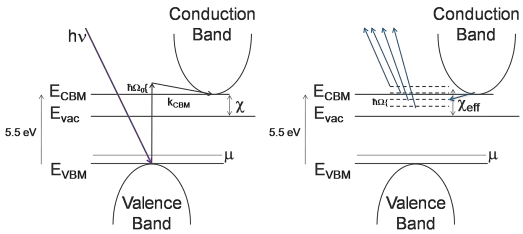


Above) Schematic of ARPES system, including photon source and energy analyzer
Below) Picture of U13 system, showing synchrotron beam path (blue) laser beam path (purple) and spectrometer entrance (yellow). The sample stalk is in the center of the chamber, and can rotate to vary the electron angle acquired by the spectrometer.

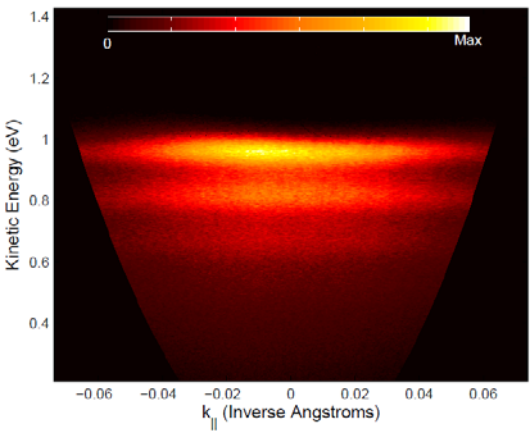


Laser ARPES

Laser (6 eV) photons are below the direct transition band gap. Thus photoexcitation to the CBM entails a second order process involving the absorption of a photon followed by emission of a phonon of energy $\hbar\Omega_0$ and finite momentum k_{CBM}. Under low energy laser excitation this process occurs in the bulk (~1 μm) of the sample.



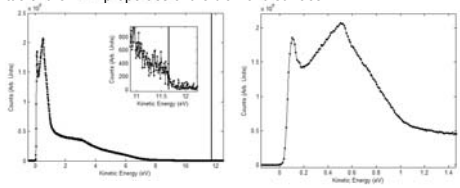
Left) Photoexcitation of an electron to the conduction band minimum (CBM)
Right) Emission process from the CBM, including phonon emission



ARPES spectrum acquired using the 6.01 eV laser. The overall "bowl" shape of the spectrum results from scaling between emission angle and $k_{||}$.

Synchrotron ARPES

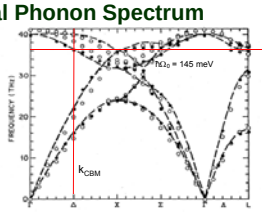
Synchrotron (16 eV) photons are absorbed in a very shallow region near the diamond surface (~ 1nm). Most of the electrons emitted do not thermalize to the CBM, leading to an energy distribution curve that is indicative of the diamond valance band density of states, but says very little of the NEA properties of the diamond surface.



Density of states for H:C(B)[100] at 16 eV photon energy. E_F is marked by the dashed line at 11.73 eV yielding a work function ϕ = 4.27 eV. Inset: a zoom of the near-E_F spectrum. The low KE peak is generally associated with NEA (secondary) emission.

Diamond Optical Phonon Spectrum

The zone center optical phonon for diamond has an energy of 165 meV. However, the phonon connecting the momentum position of the CBM with the zone center has a lower energy (145 meV), which exactly matches the energy spacing observed in the Laser ARPES (derived from the FC analysis).



Phonon Dispersion Curve (E.O. Kane, Phys. Rev. B **31**, 7865 (1984)

CONCLUSIONS

The electron amplifier has achieved emission gains in excess of 180
The energy spread of the emitted electrons is determined by the NEA value of the diamond (-1 eV)
As an indirect band-gap material, emission of electrons from the CBM requires phonon participation, and results in an EDC with discrete peaks with spacing of 142±5 meV
The e-ph coupling constant was determined to be 1.1 ± 0.01

REFERENCES

J. D, Rameau, J. Smedley, E.M. Muller, T. Kidd, P. Johnson, Phys. Rev. Lett., to appear ~April 8, 2011, arXiv:1103.1897v1
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