MODELING THE PERFORMANCE OF A DIAMOND CURRENT AMPLIFIER FOR FELS

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Abstract

A diamond current amplifier reduces demands on photocathodes for FELs by increasing the apparent QE of photocathodes through the use of secondary emission amplification in a diamond flake. Characteristics of the emerging bunch depend on diamond properties and operating conditions. A study of electron bunches subject to scattering and space charge is considered with regards to impact on yield, transit time, and rise/fall characteristics.

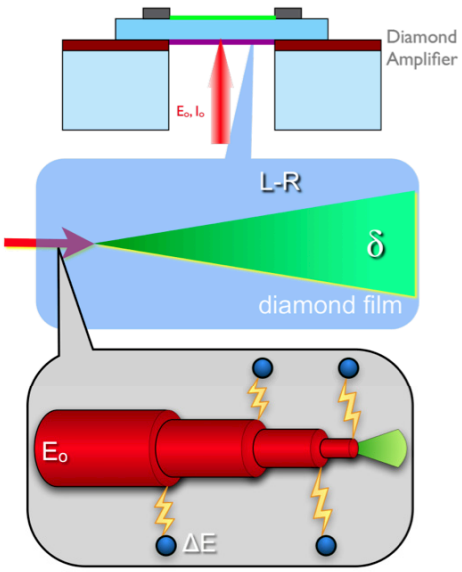

Figure 1: Schematic of the diamond amplifier: secondary electrons are generated by an incident primary beam in a thin (< 10 μm) diamond film.

BACKGROUND

In secondary emission, energy loss and range of penetration can be related to the primary beam energy by assuming that the primary beam knocks core electrons from the carbon, and that the knocked electrons have an energy about 2.5 times the band gap. These electrons are followed using standard Monte Carlo methods as they scatter, then accelerate, then scatter, and so on through a thin diamond film, in order to estimate effects of boron doping and applied field effects on the transit time.

The initial conditions of the electrons are specified by using the Bethe model for how the energy of the several keV primary beam is lost in the diamond: N electrons are deposited, where N is the number of secondaries a 3-5 keV electron can generate, at z_j, where z is measured with respect to the surface, and

$$z_j = -\int_{E_j}^{E_o}\left(\frac{dE}{dx}\right)^{-1} dE \approx \frac{E_o^2 g(E_o) - E_j^2 g(E_j)}{48\pi N (R_\infty a_o)^2} \quad (1)$$

where the introduced function $g(E)$ is shown in Figure 2, $Z = 6$ for carbon, and R_∞ is the Rydberg energy.

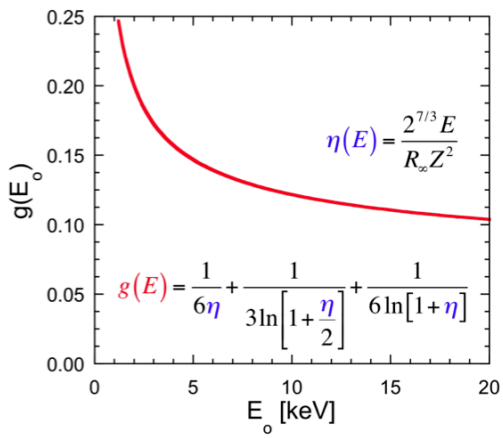

Figure 2: Schematic of the diamond amplifier: secondary electrons are generated by an incident primary beam in a thin (< 10 μm) diamond film.

MONTE CARLO

Once the electrons are generated, they are allowed to propagate through the diamond film under an applied field subject to scattering events. The scattering mechanisms considered are impurity, acoustic, and optical phonon scattering, for which the last is the primary energy loss mechanism. Acoustic phonon energy exchanges are meV level, and so the energy exchange is ignored: the only effect is the redirection of the electron. Non-polar optical phonons are the primary energy loss mechanism, and each phonon takes (or adds) an energy of approximately 0.16 eV. Ionized and neutral impurity scattering are present but not dominant.

Boron atoms always present, and when an applied field is present, they charge and so change the electric field within the diamond. A field a the back contact of the diamond (where the secondaries are generated) is required to increase yield but ionized impurity density shields it and if too high, can eliminate it, because charge present within the diamond film leads to band bending. The thickness over which an externally applied field Fvac is completely shielded due to charge present is given by

$$w = \frac{\varepsilon_0 F_{vac}}{N_A^+ q^2} \approx 0.553\mu m \frac{F_{vac}\,[\mathrm{MV/m}]}{N_A^+ \left[10^{14}\mathrm{cm}^3\right]} \qquad (2)$$

The effect of boron doping acts to slow the transit of the pulse across the diamond, as indicated in Figure 4

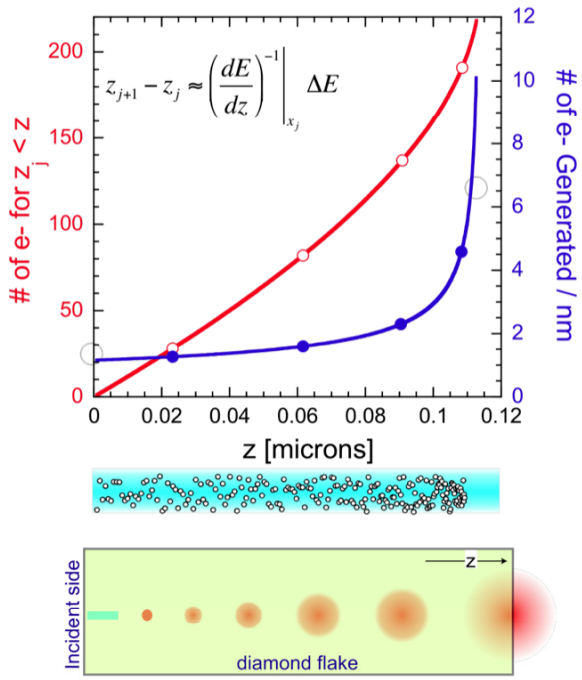

Figure 3: (top) Deposition of electrons in diamond flake, their relative density of deposition (middle), and how they migrate through the flake (bottom).

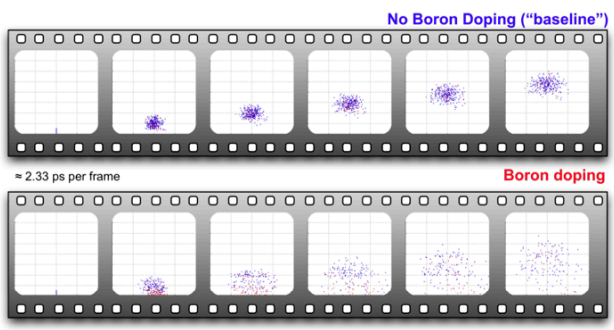

Figure 4: Schematic of the diamond amplifier: secondary electrons are generated by an incident primary beam in a thin (< 10 μm) diamond film.

The yield, or how many electrons are emitted for each primary electron incident, is affected by several factors. First, right after creation of the secondaries, a fraction of them are directed towards the back contact where they are lost. Under the grip of the field, the bunch of charge is pulled through the diamond film, where it diffusively expands as it migrates at a constant velocity as a consequence of scattering. Simulation indicates that at a field of 10 MV/m

In Figure 4 it is seen that as the charge distribution transports under field, it also expands. Thus, the longer the distribution of charge remains in the diamond layer, the larger it becomes, and consequently, when it emerges from the diamond flake, the rise-fall time of the current will be dependent upon the transit time. Results of the simulations are shown in Figures 5-7, which show the presumed potential profile as a function of doping and its consequent impact on the transit time, and therefore the rise-fall time of the emitted current.

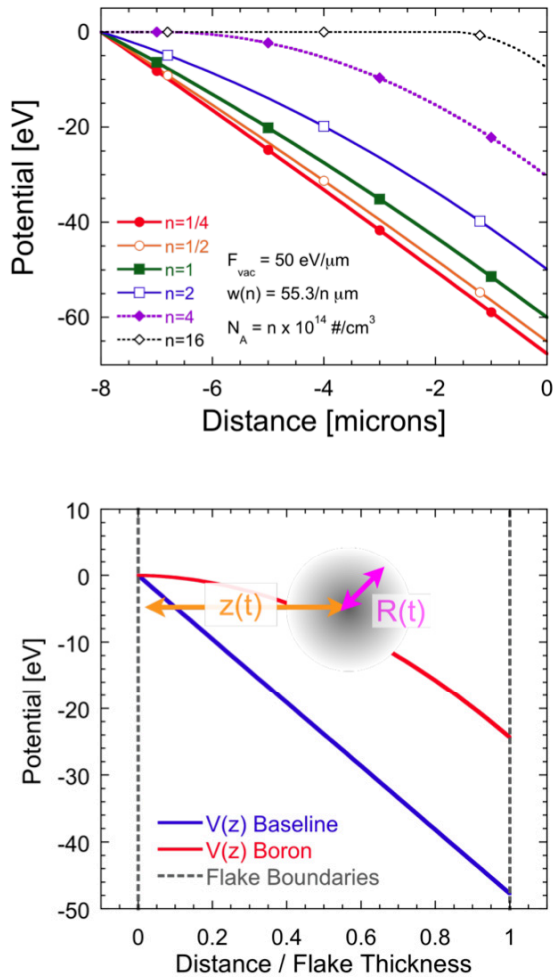

Figure 5: (top) Potential profile of undoped ("Baseline") and doped diamond at various doping levels. (bottom) The diffusive sphere R expands as square root of time, whereas the distance z is approximately linear with time.

CURRENT AND TIME DEPENDENT BEHAVIOR

Thus, there are three distinct time regimes that characterize current due to a single primary electron. The first, shortly after the creation of the secondaries, is short and covers losses of the energetic secondaries to the back contact. After the electrons thermalize and are pulled through the diamond film, losses to the back contact cease, and the second time regime of drift transport across

the diamond film takes place. Finally, when the expanding sphere of charge reaches the opposite side of the diamond flake, emission into vacuum occurs, and the third regime governs the emission of the bunch. The total current, and its characteristic time behavior, is then obtained by integrating over all the individual diffusive spheres, as in Ref. [4]. The regimes are schematically indicated in Figure 6.

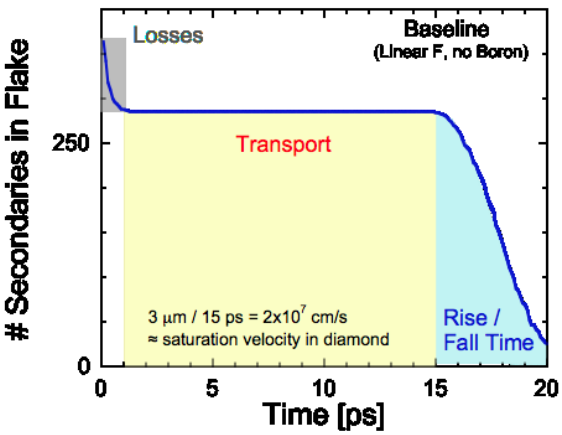

Figure 6: Different temporal regimes of evolution of bunch of electrons within a diamond flake for baseline (no doping) conditions. Current corresponds the change in the number of secondaries with time.

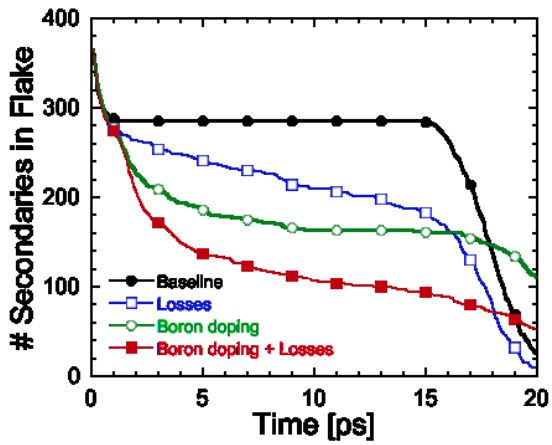

Figure 7: Different temporal regimes of evolution of bunch of electrons within a diamond flake for baseline (no doping) conditions. Current corresponds the change in the number of secondaries with time.

Four cases are now considered in Figure 7: the first (baseline) is the same conditions as in Figure 6; the second (losses) assumes an exponential loss factor in which the probability an electron is lost over time goes as $\exp(-\alpha t)$ with α = 50 ps. The third (boron doping) considers transport under band bending when the boron acceptor density is 4.7x1014 cm-3. The fourth and final (boron doping + losses) considers both the second and third conditions to hold. The yield is proportional to the number of electrons that emerge from the far side, and scales with the number of electrons present in the flake, as per Figure 7, after the losses to the back contact subside. Importantly, the losses associated with "boron doping" occur because of the greater dwell time of the bunch of electrons near the back contact where they are absorbed, and so the yield drops by comparison to the baseline, or most optimistic, scenario.

In conclusion, the degree to which acceptors are present in a diamond film affect the response time and transport characteristics. The yield is reduced as electrons are lost to the back contact, and the rise /fall characteristics are lengthened as the field within the diamond is reduced, causing bunches to take longer times to cross the film. As a consequence, doping levels must be controlled so as to maximize the internal field, and the width of the diamond film must be kept small.

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