Applications of Diamond Films to Photocathode Electron Guns and Accelerators

C. P. Beetz, B. Lincoln
ATM, Inc., Danbury, CT
and
K. Segall, D. Wall, M. Vasas, D. R. Winn
Dept. Physics, Fairfield University, Fairfield, CT
and
D. Doering and D. Carroll
Dept. Physics, Wesleyan University, Middletown, CT

Abstract

The unique thermal, chemical, electrical, surface and mechanical properties of synthetic diamond films are discussed for high current photocathode driven electron guns. The potential of diamond as a cold photocathode substrate and direct photocathode are discussed. Novel optic methods to create temporal and spatially profiled electron beams are presented.

I. INTRODUCTION

Compact laser driven electron sources of high brilliance, peak current, and cold temperatures that allow control over the spatial and temporal beam properties are of great interest to accelerator technology[1,2,3,4,5,6]. For example, a linac gun producing a bunch matched to the RF would operate without a buncher; accelerators are generally more efficient with the injected beam matched to the dynamic properties of the electromagnetic fields in the accelerator. Some accelerator techniques demand temporal and spatial properties difficult to achieve because of parasitic electrical properties. For example, in a wakefield accelerator, pulses may need to be separated by less than ~1 ns. Many of these issues can be addressed by an optically driven cathode.

We discuss 3 methods to extend photocathode electron gun technique: (1) a diamond photocathode substrate, both for heat-sinking and for rear illumination of vacuum photocathodes; (2) fiber-optic photocathode drivers to tailor the temporal and spatial properties of electron beams; (3) possibility of a robust, air-cycleable direct diamond film photocathode utilizing the negative electron affinity (NEA) properties of the diamond (111) surface.

II. DIAMOND TECHNIQUES FOR PHOTOCATHODES

A. Diamond Transparent Photocathode Substrate

Major advances have been made in high brilliance, kA/cm^2 electron beams with Cs_3Sb[7,8,9], Cs_3SbK_2[10] and other [11,12,13,14,15,16,17,18] photocathodes. A general schematic of a back illuminated laser driven photoemissive electron gun is shown in Figure 1. The primary deficit of photocathodes is the short photocathode life from thermal effects.[1,6,11] In order to reduce the thermal load and thermal shock on the photocathode, we propose a diamond film as a high thermal conductivity substrate for conventional photocathodes. The thermal conductivity of diamond films is 3-4 times higher than copper[19] at room temperature. Heat is extracted more efficiently from a diamond substrate than from any other material. The photoemission process from the photocathode also leads to thermionic emission because of optical absorption in the photocathode material. The resulting temperature rise can result in irreversible damage to the photocathode. The temperature rise of the photocathode heated by either a continuous or a pulsed laser is given by:[6]

$$\Delta T \sim 2P'/\pi rk \qquad \text{(continuous illumination)}$$

$$\Delta T \sim W/\pi r^2/(2k\rho C_v \tau)^{1/2} \qquad \text{(pulsed illumination)}$$

where P' is the continuous absorbed power, r is the optical spot radius, k, ρ and C_V are the thermal conductivity, density and specific heat of the photocathode and substrate combination, W is the absorbed pulse energy and τ is the pulse duration. For typical metal substrates, k ~ 1 W/cm°K in the vicinity of room temperature, if r ~ 10^{-4} cm and P' ~ 100 mW, the temperature rise would be on the order of ~ 600°C. Pulsed operation with $W/\pi r^2$ ~ 0.1 J/cm^2 and ρCv ~ 1 J/cm^{3}C would lead to a temperature rise of ~ 500°C. Cs_3Sb and Cs_3K_2Sb cannot be used as photoemitters at temperatures above 180°C. If we substitute a polycrystalline diamond film as the photocathode support, where k ~10-20 W/cm°K[19] then the temperature rise is ~x5-x7 lower, and the photocathode should continue to operate. The temperature rise of the photocathode is higher with other nonmetallic transparent substrates (sapphire, etc.). Diamond also has a relatively low dielectric constant ($\varepsilon/\varepsilon_0$=5.5), very high breakdown strength (10 MV/cm), and controllable $\rho \sim 10^{13}$-10^{-3} Ω-cm (see below).

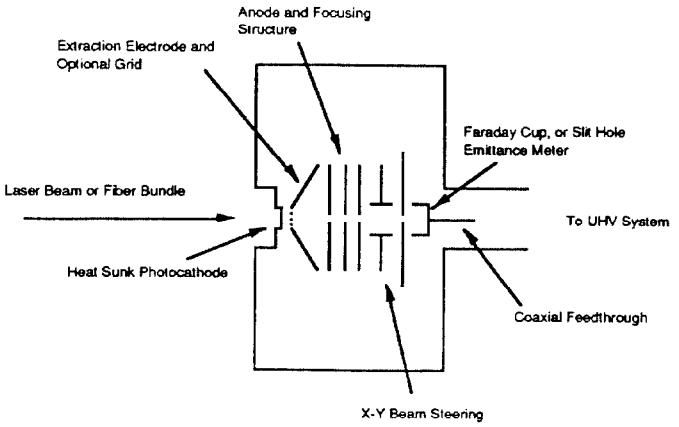

Fig. 1.Schematic of a laser driven photoemissive electron gun.

Moreover, the very low diffusion coefficients of foreign atoms into the diamond lattice, the chemical inertness of diamond surfaces, and the ability to be baked at high temperature may make the cesiation and photocathode processing easier than with competing metal or ceramic surfaces. Even so, cesiation is a complex process[20],[21] and

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the lifetime of cesiated photocathodes is short, dependent on the intensity, temperature and pressure in the vacuum chamber[6]. Recent studies of Cs_3Sb lifetime showed that the optimum operating temperature range is 280 - 290°K and that the lifetime decreased by a factor of >34 on increasing the temperature to 373°K[6]. The lifetime of the Cs_3Sb also depends on pressure, decreasing by a factor of ~23 on going from $3x10^{-10}$ to $1.3x10^{-7}$ torr.[6] The use of a diamond film substrate for supporting the photocathode addresses the temperature and back-illumination issues only, and does not address the problems associated with (atmospheric) contamination. These observations point out the need for a more robust photocathode that can be cycled from UHV to atmosphere and still function after bakeout.

B. Diamond Film Photoemitter

A second approach to preparing a more robust photoemitter is to consider the diamond (111) surface which has been shown to have a negative electron affinity (NEA).[22],[23] The conduction band of diamond (111) is ~0.7 eV above the vacuum level, thus permitting electrons to escape from the diamond on excitation with band gap radiation (5.45 eV). This has the interesting prospect of making a photocathode that could be exposed to air at atmospheric pressure and not lose its photoemission properties. The (111) surface exhibits a (1x1) LEED pattern and appears to be terminated with hydrogen. This surface is stable up to ~ 1000°C before hydrogen desorption and subsequent relaxation occurs, thus permitting a simple photocathode design consisting of an epitaxially grown lightly B doped diamond layer on a single crystal diamond substrate. Figure 2 shows an SEM of a typical diamond film grown by us, used for diamond electro-optics. Note that polycrystalline diamond films have predominantly (111) crystallites. The major advantage is a more robust photocathode whose emission properties are potentially even less susceptible to degradation by temperature. Such a photocathode could be exposed to the air and subsequently baked in vacuum and retain its photoemission properties. During the course of this work, prototype photocathodes that we have investigated have been repeatedly exposed to air, and continue to function without processing, possibly a boon to electron gun practice.

Our preliminary investigation used diamond (111) oriented single crystal and textured polycrystalline CVD films as NEA photoemitters in a vacuum system. We know of one other report[21] on photoemission properties of diamond. The detectable onset of photoemission occurs at ~280-290 nm, 60-70 nm above the intrinsic band edge. By 260 nm, the quantum efficiencies are still low, $\sim 10^{-7}$-10^{-8}, but having risen by about x100, over 20-30 nm. Our light source cuts off below 260 nm, so the data was limited. However, we expect for typical photoemission scaling that the efficiency would rapidly increase below 220nm, to $\sim 10^{-3}$-^{4}, where strong absorption occurs. The polycrystalline film had better emission properties. Research issues that need to be addressed are: (1) can the quantum efficiency improve in better synthetic polycrystalline samples, with activation processes, or with bias voltage, and (2) can the diamond film substrate conduct enough current to neutralize the photocathode in <1 ns, by conductivity changes through in-situ dopants, or a thin B-doped film. Recent studies have shown that low bias voltages cause direct e^- emission from (111) surfaces into vacuum.[23]

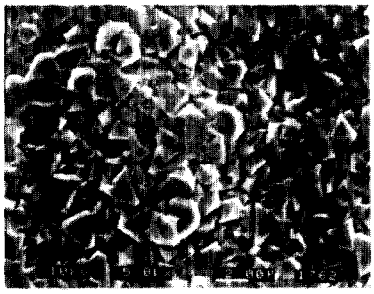

Fig. 2: SEM of a diamond film grown by us for diamond electro-optics. The crystallites are ~1-2 μ in size, ~50% (111).

III. FIBER OPTIC SPATIAL/TEMPORAL BEAMS

The second area of interest is to control the spatial and temporal properties of the photocathode-generated electron beam. A primary benefit of the diamond film is its transparency, ie the optical pulse can be injected from the back end of the gun, without intrusion into the downstream. We therefore propose back-coupling a dense fiber-optic array directly to the photocathode through the diamond film, driven by an array of laser(s). The coupling of the power of a laser to optical fibers can be up to ~20%, with kilowatt/mm^2 beams available from a single fiber. The spread in the spot size through a small fiber across a 0.5-3 mm thick film would be negligible and correctable. The vacuum standoff strength of the diamond film is good over several cm^2 of atmospheric pressure. (Note: small single-mode fibers with a small N.A. can interpenetrate the vacuum region for front illumination, with a very good HV standoff.)

The fiberoptic bundle would be fashioned to create the spatial and temporal emission current profile across the cathode, for example, to produce spatially hollow, smoothly shaped or multiple pulsed beams by adjusting the light intensity and temporal properties in the fiber array. For example, in Figure 3, by trimming the fibers into 2 bundles of 2 discrete lengths (delay times), a single short laser pulse injected into the bundle will produce 2 optical pulses, with their start separated by a time delay $\tau=\ln/c$.

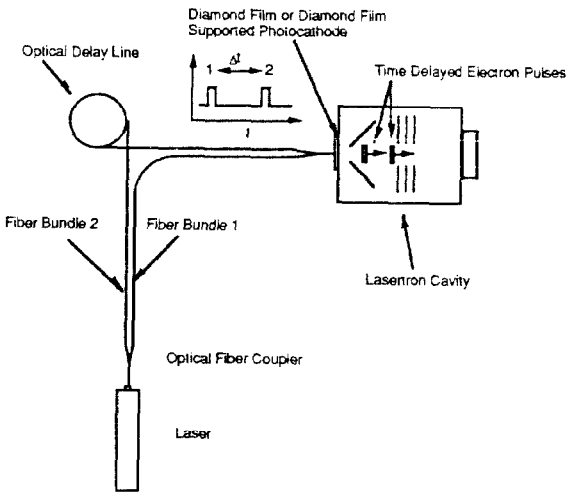

Figure 3. Fiber optic delay lines producing a double electron beam pulse.

A second example would be to arrange the fibers in a spatial pattern, such as a hollow beam. By appropriately adjusting the length, intensity and position of the fibers on the back of the photocathode, a beam of any property can be formed (granular on the beamlet size - the emittance properties of a beamlet are given partially by the photoemission angular dependence, which is ~$\cos^2 t$, where t = angle to the normal of the surface).

A fiber-optic photocathode could have applications for FELs, microwave generators, direct drive & high frequency RF linacs, bunched beam-cavity & beam-beam interaction studies, and turbulent electron flow. The beamlets may provide a method of increasing the acceptance efficiency and reduce the electron beam power subtended by the grid in a gridded-gun. Narrow double pulses may allow studies of wakefield and beam breakup effects in conducting and dielectric channels. Variable optical delays producing multiple driving & probe beams is unique. Furthermore, short/multiple pulse electron sources can be used in several surface and materials analysis techniques.

IV. DIAMOND GROWTH AND CHARACTERIZATION

Recent advances in chemical vapor deposition (CVD) of diamond from dilute hydrocarbon in hydrogen gas mixtures have shown it is now possible to deposit polycrystalline diamond films over large areas (~8 cm dia.), with a predetermined impurity concentration via in-situ doping [24],[25], at a significantly lower cost than high pressure synthetic diamond. Polycrystalline films have demonstrated room temperature thermal conductivities as large as 10-20 W/cm°K[19], comparable to type Ia natural diamonds above room temperature. The electrical resistivity of diamond films can be varied from ~10^{13} to 10^{-3} Ω-cm [26,27,28,29,30,31], depending on the dopant concentrations (both p- and n- type).

Our diamond films were grown using either hot filament-assisted or plasma-assisted CVD (polycrystalline films) or MBE (B-doped single crystal homoepitaxial films) using custom-built equipment. Boron is the shallowest (~360meV) known acceptor species dopant in diamond., and increases the film electrical conductivity, in order to make a good cathode connection (ohmic contact) and modify the performance of the photocathodes. The diamond films were characterized using Raman and photoluminescence spectroscopy, SEM and X-Ray diffraction, showing little sp2 carbon or hydrogen. Ohmic contacts were deposited using the method described in [32], using Ti and Au.

V. CONCLUSION

Because of its high thermal conductivity, optical transparency, controllable conductivity, breakdown strength, and negative electron affinity, diamond is an interesting material for applications in compact electron beam accelerator technology, possibly enhancing the potential of novel beam forming methods utilizing optical fiber driven photocathodes.

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