DEVELOPMENT AND CHARACTERIZATION OF DIAMOND FILM AND COMPOUND METAL SURFACE HIGH CURRENT PHOTOCATHODES

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Abstract

High current photocathodes operating in vacuum environments as high as 8xE-5 torr are being developed at Los Alamos for use in a new generation of linear induction accelerators. We report quantum efficiencies in wide bandgap semiconductors, pure metals and compound metal surfaces photocathode materials illuminated by ultraviolet laser radiation.

INTRODUCTION

The first axis of the DARHT (Dual Axis Radiographic HydroTest) accelerator [1] is a 20 MeV, 4 kA electron beam linear induction accelerator (LIA) producing a single 60 ns pulse. At the final focus magnet of the accelerator the beam is focused to a 1.2 mm spot on a high Z target producing intense bursts of bremsstrahlung radiation with a flux of 1000 R at 1 meter from the target.

The ability to focus the high current electron beam to the 1 mm spot is dependent on the on beam energy dispersion, centroid motion and emittance. The beam emittance is determined by the injector source temperature.

The cathode presently used in the DARHT injector is a velvet field emission cathode producing an electron beam with a temperature above 100 eV. Experiments at the DARHT Integrated Test Stand (ITS) now demonstrate that with the velvet cathode injector and the initial 5.75 MeV acceleration a beam emittance of 0.15 π cm-rad results in a focused spot radius of $\cong$ 0.5mm. This emittance measurement meets the baseline physics design criteria but does not provide
a sufficient margin of safety should unforeseen conditions in the full system lead to emittance growth, increased energy spread or centroid motion.

The DARHT accelerator system architecture includes the use of plastic insulators in the accelerator and in the 4 MeV injector. The use of plastic dielectric materials along with the extensive use of elastomer vacuum seals results in the need to operate the electron beam vacuum diode at total pressures of 1E-6 torr.

Traditionally used low temperature, high current electron beam sources, such as thermionic and multi-alkali metal cathodes will not operate in the present DARHT vacuum environment.

The development of a photocathode operating at modest vacuum pressures has been identified as the best technology to gain the needed reduction in beam temperature for the DARHT 1st axis. A factor of 10 reduction in beam temperature would reduce the emittance contribution to the spot size by 1.8.

Investigations into the development of photocathodes for the DARHT moderate vacuum environment has been broken into two areas. The best understood approach, with the simplest emission mechanisms is the use of low work function bare metals [2,3]. This approach is reasonably straight forward but requires high ultraviolet laser fluences due to low quantum efficiencies of metals even at the highest photon energy laser wavelength available for practical application (ArF, 193nm) [4]. The second, and higher risk approach is to develop new high quantum efficiency photocathodes based on the emerging technology in wide bandgap semiconductors, particularly diamond films.

The photoelectric [5] processes differ considerably between metals and wide bandgap semiconductors such as diamond. In metals the photoelectron created within the solid has an energy above the other electrons at thermal equilibrium and are commonly referred to as hot electrons. The photoelectron is likely to be scattered elastically and inelastically by other electrons because of the abundance of free electrons in a metal and thus approach thermal equilibrium within a short distance. The scattering processes limit the emission to an escape depth of only a few atomic layers. The emission process in metals can be enhanced by increasing the surface temperature of the metal thereby statistically increasing the number of electrons above thermal equilibrium at the surface/vacuum interface.

In a semiconductor, photoemission takes place when a photon is absorbed and converted into a free electron with sufficient energy to cross the bandgap from the valance to the conduction band, in diamond this energy is ~5.47eV. The electron must now overcome the electron affinity of the material to escape into the vacuum level. This process is accomplished by downward band-bending through boron doping of the bulk material and hydrogen surface termination to move the vacuum energy level below the conduction band allowing the electron to fall into the vacuum level thus resulting in a surface with a negative electron affinity (NEA) [6].

Diamond films exhibit unique physical properties, such as thermal conductivity 3 times that of Cu and can withstand over 1 joule/cm2 of 193nm laser radiation.

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EXPERIMENT

To facilitate rapid evaluation of various photoemissive materials we have assembled the PhotoCathode Test Stand (PCTS).

The PCTS has the ability to illuminate small scale samples with an ArF laser producing 193 nm (6.4 eV) laser radiation, normal to the cathode emitter surface. A d.c. voltage of 40kV is applied to the cathode. The anode/cathode gap spacing is nominally 6.7mm. The 6.0-mm-diameter laser radiation incident on the cathode surface is regulated in intensity by using a series of quartz attenuator plates at the inlet aperture to the vacuum diode. The laser fluence on the cathode can be varied over one order of magnitude allowing for photoelectron extraction at very low emission limited currents to past the space charge limit. The extracted electron current generated by the pulsed laser radiation is collected in a tubular charge collector ballasted close to ground by a radial resistor between the collector tube and the grounded anode support tube. This charge collector also contains a defining aperture to size the diameter of the laser beam and the exposed ends of three optical fibers to sample the laser fluence on a shot to shot basis. The fibers are coupled to a 193-nm-line-filtered Hamamatsu photodiode that is calibrated by substituting a pyroelectric calorimeter in place of the photocathode test sample. The photocathode test samples are heated to 125 deg C by means of intense incandescent light introduced into the vacuum through a Pyrex light pipe. The radiant heat is incident on the back surface of the photocathode substrate. The planar diode is configured with an easily removable standard cathode holder. The anode is a flat fine wire mesh >93% transparent tungsten screen. The vacuum chamber is pumped with a 1500 L/s cryo pump and a residual gas analyzer is used to monitor the constituent background gas species.

Recent test data has been acquired on 8 different sample types listed in Table I. Since aluminum has been tested in larger scale systems and has been investigated more extensively in recent years, it was chosen as the baseline standard for purposes of comparison to other materials. Aluminum has a work function of 4.2 eV and a melting point of 660C. Samples were prepared by micro-machining (diamond turning) a 6061 alloy and then applying a 2000 angstrom layer of pure Al by physical vapor deposition (PVD). Data were taken at two temperatures, ambient and ~125C [7,8]. Another aluminum sample was prepared in the same manner with the exception that the surface was glass bead blasted, creating a fine pitted surface structure prior to the PVD process. This process has the effect of increasing the surface area exposed to the laser radiation and may enhance multi-photon effects.

The two other metal samples are compound metal surfaces made of samarium and aluminum created with a flow through ion system in conjunction with metal vapor condensation. Samples were created with varying ratios of Sm/Al. Samarium was chosen as an alloying material due to the low work function (3.2 eV), is nearly a total absorber at the ArF 193nm wavelength and has a melting point 400C higher than Al.

The three semiconductor samples are two polycrystalline, boron doped diamond films (bandgap=5.47 eV) and a single crystal-silicon-carbide-wafer doped with aluminum (bandgap=3.03 eV).

One boron doped polycrystalline diamond sample was grown on a molybdenum substrate using a microwave assisted chemical vapor deposition process. The other boron doped polycrystalline diamond sample was grown on P type silicon using a hot filament vapor deposition technique.

RESULTS

The summary table below is based on data sets with a minimum of 100 pulses for each sample measured at 10 different laser energies ranging over an order of magnitude. The average quantum efficiency is obtained by fitting a line to peak current density as a function of peak laser power for data which is emission limited. The slope of the line multiplied by the 6.4eV photon energy yields the quantum efficiency (Q.E.). Figure 1 is a overlay of the data and linear fits for two samples with the highest quantum efficiencies.

Sample type	Sample temperature (degree C)	Ave. Quantum efficiency (electrons/photon-%)
Pure Al	25	0.061
Pure Al	125	0.076
Bead blasted Al	125	0.049
Al/10%Sm	125	0.029
Al/50%Sm	125	0.027
SiC (single crystal)	80	0.013
Diamond/Mo (polycrystal)	125	0.028
Diamond/ P type Si (polycrystalline)	125	0.325

Table 1

If polycrystalline diamond mounted on p-type silicon were used as a photocathode to produce a 3kA-60ns-electron beam with a 76.2mm cathode, the necessary laser energy on the photocathode would be 0.36 J. For a similar aluminum cathode the necessary laser energy would be 1.5 J.

Workers have reported quantum efficiencies above 1% for boron doped polycrystalline diamond on Si [8] and 4% for natural type IIb single crystal diamond [9].

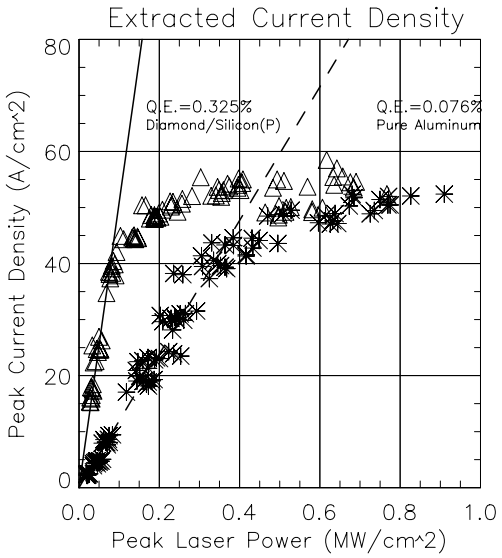

Figure 1 Peak current vs peak laser energy for two samples.

CONCLUSIONS

The photoyield of the polycrystalline diamond film grown on P type silicon is significantly higher than the other candidate materials tested.

The high photoyield of polycrystalline diamond, scaled to the DARHT size cathode will produce 3 kA beam with a laser fluence of 0.36 joules in a 60 ns pulse. This low fluence will allow the use of ultra-high reliability, commercially available excimer lasers which will have a significant impact on the total system reliability.

Large area growth of polycrystalline diamond films has been demonstrated and are presently available from private industry.

Follow on experiments will focus on photoemission from polycrystalline diamond as a function of temperature, illumination uniformity and the diamond/substrate contact potential.

Other issues to be investigated will include high current electron emission stability and emission effects related to constituent vacuum background gasses.

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