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ADVANCES IN DC PHOTOCATHODE ELECTRON GUNS

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Abstract. At Jefferson Lab, a DC photoemission gun using GaAs and GaAs-like cathodes provides a source of polarized electrons for the main accelerator. The gun is required to produce high average current with long operational lifetimes and high system throughput. Recent work has shown that careful control of the parameters affecting cathode lifetime lead to dramatic improvements in source operation. These conditions include vacuum and the related effect of ion backbombardment, and precise control of all of the electrons emitted from the cathode. In this paper, we will review recent results and discuss implications for future photocathode guns.

INTRODUCTION

At Jefferson Lab, a DC photoemission gun using GaAs and GaAs-like cathodes provides polarized electrons for the main accelerator. DC guns hold a distinct advantage for systems that require high average current as opposed to those requiring high peak current with a low duty factor. The polarized source runs at 100 kV and can provide multiple, independent beams to three experimental halls with a total average current of up to 200 μA and can deliver as much as 16 C of electrons per day.

The ability to deliver these high average currents for extended periods of time has a large impact on machine availability at Jefferson Lab. On the main accelerator, 70-80% availability is necessary to meet the full experimental schedule of the nuclear physics community so little time can be spent on cathode maintenance. Progress has been made in the last year in understanding and controlling the conditions that affect cathode lifetime: vacuum, crystal damage from ion backbombardment, and precise control of halo electrons. The polarized source now routinely reaches operational 1/e lifetimes of 100-200 hours for ~150 μA average beam currents and upgrades are being planned to increase this to over 500 hours.

In this paper, recent results from the polarized source will be presented showing details leading to dramatic improvements in the operational lifetime of the source. Properties related to the performance of future photocathode guns will be discussed.

LIFETIME ISSUES

Photoemission electron guns utilizing GaAs (or GaAs-like) cathodes have been in operation for over 20 years as a source of polarized electrons [1]. They are notoriously difficult to operate and maintain due to the ultra-high vacuum environment necessary for activating the cathode to obtain a negative electron affinity (NEA) surface. Notably the group at SLAC [2] has made significant progress in recent years with increasing the polarization, lifetime, and operability of these sources. Their introduction of a load-lock chamber has eliminated many of the problems associated with wafer changes such as repeated high temperature bakeouts and high voltage processing. Unfortunately, many of the lessons learned there for producing high peak current, low duty cycle beams do not transfer directly to labs like Mainz, MIT-Bates and Jefferson Lab; these labs must produce high average current beams.

Lifetime is a measure of the time it takes for the QE to degrade to 1/e of its initial value. A more useful measure for labs delivering high average current is the charge delivered before the QE degrades by 1/e. Typical numbers for the Jefferson Lab polarized source are 100-200 hours for a 100 μA beam, or 36-72 C. The dark lifetime is the performance of the cathode when it is not exposed to illumination. A long dark lifetime measures the quality of the vacuum and surface chemistry is the primary mechanism of degradation. The dark lifetime with high voltage applied may be worse due to field emission from high field points. Using diamond-paste polished titanium electrodes, the maximum field emission current is less than 1 nA at 100 kV, substantially lower than reported elsewhere [2]. The overall lifetime during beam delivery is a complicated function of the vacuum conditions in the gun and the electron beam optics.

One particular physical process that limits operating lifetime at high average currents was recently recognized at Mainz [3]. They found that the QE of the cathode decayed in an unusual pattern that could only be attributed to ion damage. The process is illustrated in figure 1. An electron orbit from off-axis on the GaAs wafer is shown being accelerated towards the anode. Along its path, an electron has some probability of ionizing the residual gas in the chamber. Subsequently these particles

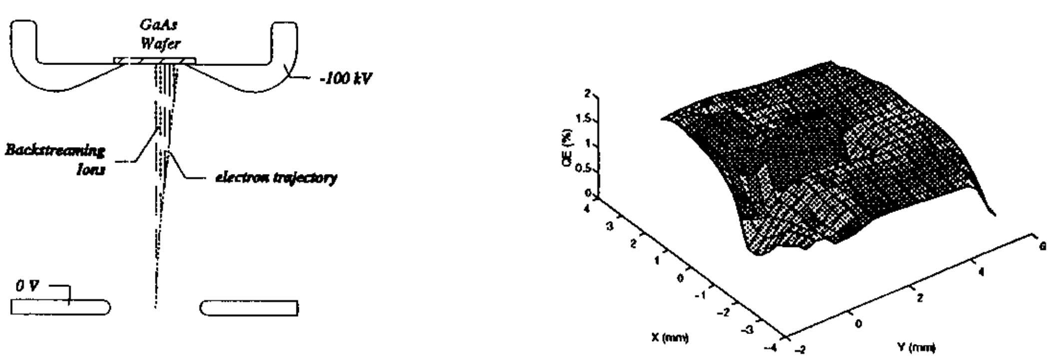

Figure 1. Model for ion backbombardment and a quantum efficiency scan over the wafer showing the resulting damage

are accelerated straight back (due to their much larger mass) towards the wafer where they cause crystal damage. The plot in the right side of figure 1 shows the QE profile over part of a wafer (from this lab) from which over 20 C was extracted. The laser beam was located at x=0 mm and y=2.3 mm and the QE trough from there to the center of the wafer illustrates the effect of the crystal damage.

SIMPLE MODEL FOR ION DAMAGE

The ionization rate as a function of kinetic energy, R(E), can be calculated assuming that the residual gas in the chamber is molecular hydrogen at some pressure P as

$$R(E) = I\sigma(E)\rho\Delta z = I\sigma\rho\frac{\Delta z}{\Delta E}\Delta E$$

$$\rho(m^{-3}) = 3.54\times 10^{22} P(Torr)$$

where σ is the ionization cross section for e^- on H_2 (see figure 2), I is the beam current, ρ is the H_2 gas density, and $\Delta E/\Delta z$ is the average accelerating gradient in the anode-cathode region. From this one can calculate the total integrated ionization rate as a function of pressure or the total rate as a function of E for a given pressure (see figure 3).

For the present geometry, the anode and cathode are separated by about 60 mm with an accelerating gradient of 1 kV/mm at the wafer. From the plot of integrated rate versus energy, 50% of the ions are generated between 0 and 8 kV, or within about 8 mm of the wafer surface. These ions will be accelerated straight back and implanted into the GaAs while the higher energy ions will be distributed between the location of

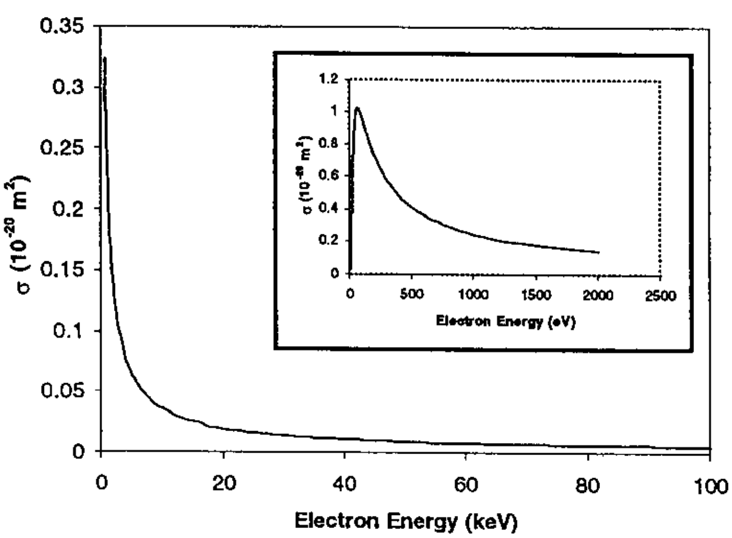

Figure 2. Cross-section for H_2 ionization by electrons [4].

the laser spot and the center of the wafer. Thus the only realistic way to reduce the number of ions (and the damage) is to reduce the pressure, since introducing any sort of fields so close to the cathode to deflect the ions away from the surface would be impractical and undesirable.

The next question is what is the damage mechanism for reducing the quantum efficiency? One possibility is that the cesium and fluorine atoms deposited on the surface to produce the NEA conditions are sputtered away by the ions. In the limited operation history of the polarized gun, adding more cesium improves the QE in the damaged region and the wafer as a whole, but it never fully recovers. This implies that a substantial portion of the damage occurs below the surface. Calculation of sputter yields for protons on GaAs using the program SRIM [5] indicate at most 1 or 2 sputtered atoms per 100 incident protons are produced, which may account for some of the photoresponse reduction.

A more likely candidate is physical damage to the bulk crystal from the implanted ions. Fortunately, since implantation of H^+ and H_2^+ in GaAs is a commonly used technique to induce damage to alter its electrical and optical properties, a rich literature exists. One important parameter is the range of the ion in the material: the range is the average distance the ion will travel before it stops. Atomic displacements near the end of the ion range give rise to point defects that absorb light and trap carriers [6]. For protons implanted in GaAs, the range varies roughly linearly from 0 (at 0 eV) to 0.8 μm (at 100 keV) with a spread of 10 to 20% in the average range (calculated using SRIM). These numbers have been experimentally verified [7] and show that most of the damage occurs when the ion stops, so a 100 keV proton will do most of its damage 0.8 ± 0.1 μm deep in the crystal. Using the SRIM program, other quantities of interest can be calculated and are summarized in table 1 along with other known information.

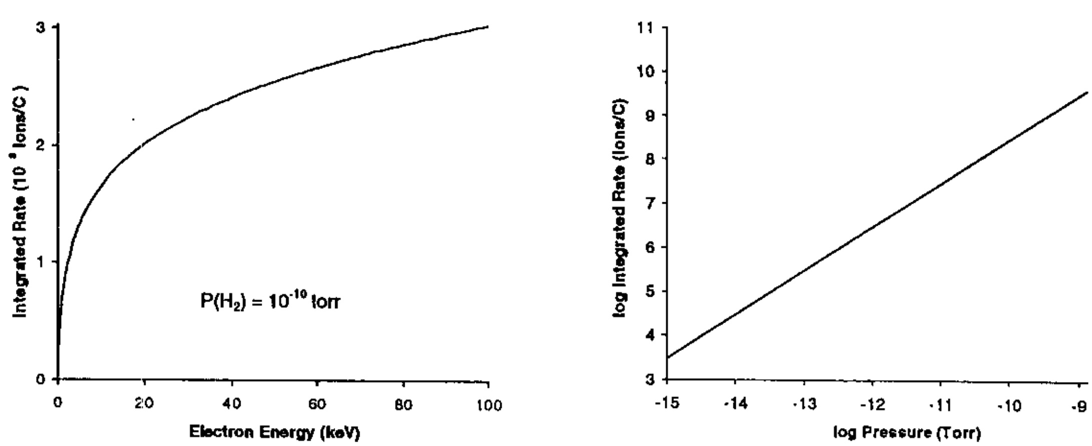

Figure 3. The integrated ion production rate per Coulomb of incident electrons as a function of energy for a given pressure and total rate for all energies versus pressure.

TABLE 1. Summary of ion backbombardment properties

Property	Result	Ref
Damage produces point defects - vacancies and deep trapping levels	Reduced carrier concentration and light absorption	[6]
More vacancies produced as E increases	Higher energy does more damage	SRIM
Damage occurs at $R(E)\pm\sigma_R(E)$	Higher energy produces deeper damage	[7]
Sputter yield is low	Some NEA surface modification	SRIM
Damage for E > 500 eV does not disappear with annealing	QE will not completely recover with annealing	[8]
H_2 dissociates on impact to yield 2 protons each with 1/2 the energy	Damage occurs closer to the surface	[7]
Up to 20% of the ions are backscattered out of the crystal for energies below 10 keV	Reduced number of damaging ions for low energy	SRIM
50% of the ion dose occurs within 8 mm of the surface	Low energy damage occurs at the laser spot	Calc

TABLE 2. Experimental observations related to ion damage

- QE degradation at the laser spot
- QE degradation along a trough towards the wafer center
- Visible wafer damage indicates a change in index of refraction
- QE away from the laser spot degrades little or not at all
- Addition of Cs improves QE over the whole wafer, but recovery is not complete
- Annealing removes most of the damage. Dimples in the QE are still visible at the previously damaged locations

These observations can be used to explain the effects seen in figure 4. A cross section through the quantum efficiency 'holes' in the cathode is shown in figure 4(d). The lines plotted on the data are inverted Gaussian distributions with a width equal to the laser spot size convoluted with the probe laser size for the QE measurements. This demonstrates that the low energy spatial ion distribution matches the initial laser size within a few mm of the wafer surface where half of the ions are produced.

The shape of the QE trough (see figure 4(c)) is more difficult to explain. Using results from PARMELA and the ionization cross section, the energy distribution of the resulting ions along the electron path can be mapped onto the surface between the location of the laser spot and the electrostatic center of the wafer. To determine the relative amount of damage along the wafer, several factors contributing to the quantum yield need to be considered. The rate calculations predict that most of the ions are produced at low energy, but the flat QE trough indicates that the total damage as a function of energy is roughly constant. By folding together the properties mentioned in Table 1 along with the fact that the absorption depth for light in GaAs is ~1 μm, a qualitative fit to the QE trough can be made (solid line in figure 4(c)). Further calculations are underway to understand the damage mechanisms in a quantitative fashion.

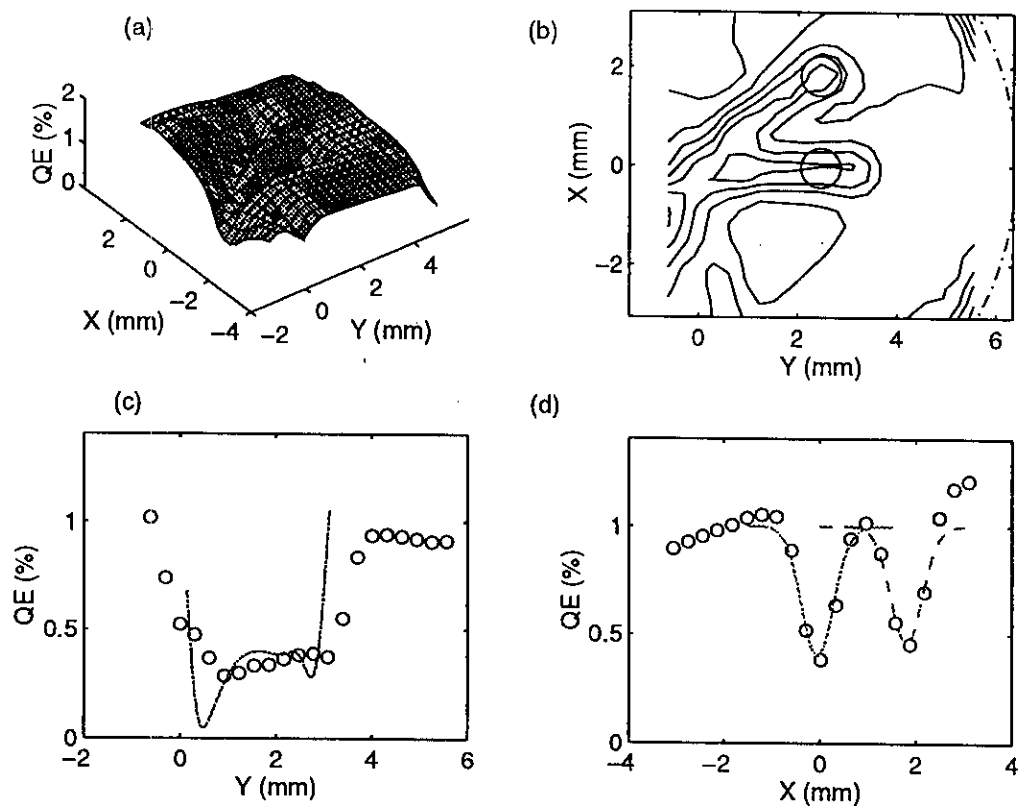

Figure 4 Quantum efficiency scan data after extended running from two spots (a). The contour plot (b) shows the location of the two laser spot positions (small circles) and the edge of the wafer (dashed line). The bottom plots show cross sections through the trough (c) for X=0 mm and through the two spots for Y=2.3 mm (d).

From the above observations, it is clear that if ion damage is the rate limiting effect for cathode lifetime, the most straightforward way to increase the lifetime is to lower the pressure in the anode-cathode gap where the ion production occurs. There are several avenues one can take to achieve very low pressures: careful attention to ultrahigh vacuum design; careful material choices; and increased pumping speed. For our present gun, we have taken the brute force route of increasing the pumping speed as much as possible. To do this, the anode-cathode region was surrounded by ten getter pump strips (S.A.E.S Getters, model WP590 formed with ST707 alloy) with a total pumping speed of approximately 4000 L/s of hydrogen. Since the sticking probability for getters is 10-20%, the geometric arrangement of the pumps is critical. The getters are arranged symmetrically around the anode-cathode area with a mesh screen to shield the sharp edges from the high voltage (see figure 5).

There is presently no reliable way to measure the pressure in the region of interest, but an extractor gauge located outside of the getter array reads in the low 10^{-12} Torr range. The quality of vacuum can be ascertained by studying the QE scans in figures 1 and 4. A millimeter from the edge of the laser, the quantum efficiency does not noticeably drop relative to its initial value after drawing many tens of Coulombs from the main spot. In fact, we are in the unique position of being able to study bulk

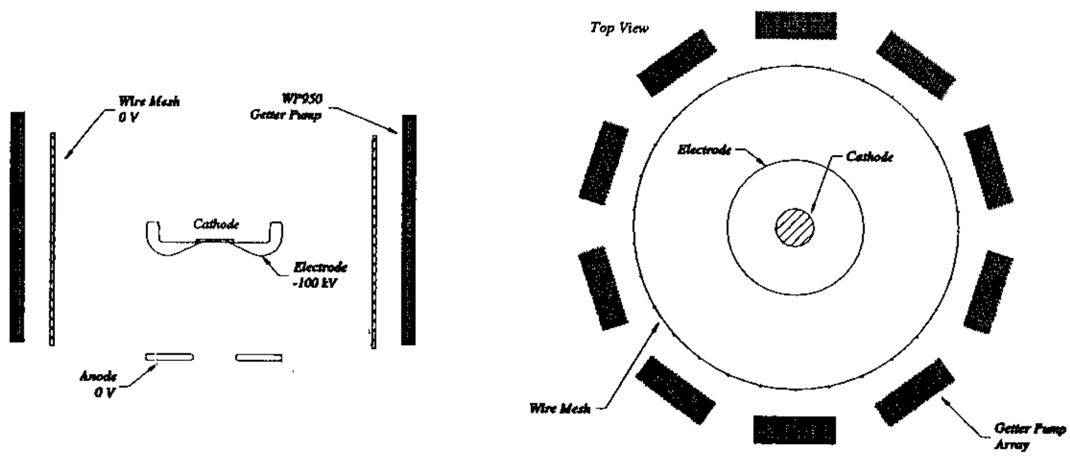

Figure 5. The getter pump arrangement in the anode-cathode region.

semiconductor damage mechanisms and damage rates. If the residual gas density and composition near the cathode were known, the amount of damage as a function of energy and number could be determined. Conversely, if the damage mechanisms were quantified, the pressure near the cathode could be measured.

CONTROL OF HALO ELECTRONS

Another important issue for obtaining long lifetimes is the precise control of all electrons that leave the cathode. Any electron that can strike a surface in the gun or beamline can lead to an increased vacuum load in the anode-cathode region due to electron stimulated desorption. The problem is particularly bad here.

Many guns utilize the entire active cathode area for electron emission [2]. In the Jefferson Lab gun the laser beam size (σ = 0.2 mm) is much smaller than the total cathode size (12.7 mm diameter) to provide the small emittance needed for the accelerator. Since the GaAs wafer has a high QE (1 to 10 %) over its entire area any stray light can cause unintended electron emission. The first clues to this problem were an increase in the gun pressure while extracting 100 μA beam and excessive radiation measured by Geiger tubes along the beamline (50 to 100 mR/hr). Simulations show that this was due to electrons emitted near the edge of the wafer.

The known sources of stray light in the gun chamber were investigated and eliminated without any effect on the stray electrons. Measurements of the remaining light (due to laser halo and recombination radiation) near the wafer but outside of the main spot were only down by a factor of 100. Thus for a main beam current of 100 μA there was as much as 1 μA of beam halo available to hit the walls.

Since the entire cathode area is not normally used, it was decided to mask the outer area of the wafer so that it could not be activated to high QE. At our lab, the wafers

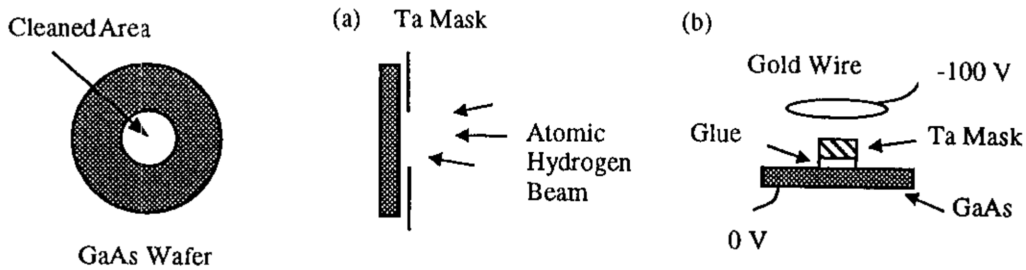

Figure 6. Selective area cleaning using atomic hydrogen (a) and anodic oxidation (b).

are cleaned using an atomic hydrogen beam [9], so masking the outer edges of the wafer from the atomic hydrogen cleaning was tried (see figure 6).

Measurement of the cathode lifetime with the selectively cleaned wafer showed dramatic improvements. The lifetime improved from 30 minutes to 20 hours, the radiation levels dropped by a factor of 100, and the pressure in the gun chamber showed no noticeable increase. This provided direct evidence that stray electrons were one of the main causes of lifetime problems. Operationally, this method of masking is not reliable for long term accelerator operations.

To reduce the QE outside the central region to tolerable levels (down by 5 to 6 orders of magnitude), the outer region is anodized to produce a thick oxide layer. The wafer is prepared by gluing a small tantalum mask at the center and placing it in a weak phosphoric acid solution (2.8 pH). A low voltage (100 -150 V) is applied between the wafer and a loop of gold wire for several minutes; this results in a thick (0.1 - 0.2 μm) oxide layer on the exposed region (see figure 6 and [10]). The glue is easily dissolved in acetone and does not damage the masked area. The oxide layer has good stability over time and has shown no effective degradation that would cause increased photoemission.

Precise optical control of all the electrons that are emitted from the cathode is the final important aspect of improving the operational lifetime of the polarized source. For a non-space charge dominated beam, the details of the electrode geometry are very important. The focussing field from the electrode angle determines the downstream beam envelope for the main part of the beam (see figure 1). For electrons that are emitted from outside the central region of the wafer, effects of misalignments and mechanical tolerances become more important. For example, the delicate GaAs wafer is slightly set back from the electrode to reduce the chance of breakage, resulting in a discontinuity between the surface of the wafer and the electrode.

Consider the following ray tracing using PARMELA [11] in which the wafer is displaced away from the electrode by a small distance. The electrode and anode are modeled as flat disks with a small step in the electrode at the location of the wafer. The electric fields are calculated using POISSON [12] and input directly into PARMELA. Without the step, the rays exit normal to the cathode as expected while increasing the step pushes the rays towards the axis. This effect determines the mask size to use for selective area cleaning as described earlier: any electron emitted outside a radius of 3 to 4 mm will cause a beam halo that can potentially strike the vacuum walls. Thus the

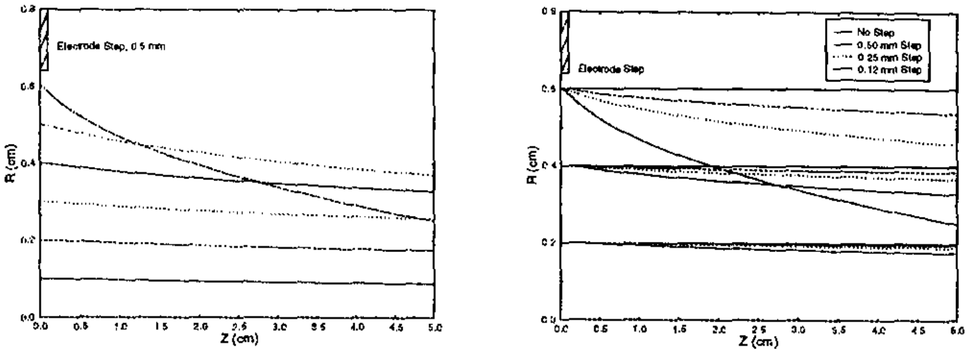

Figure 7. Simulations of a step near the edge of the cathode. The figure on the left shows the effect of a 0.5 mm step on the trajectories of individual electrons emitted at 1,2,3,4,5 and 6 mm from the center of the wafer. The figure on the right shows the effect on the trajectories at 2,4 and 6 mm for various step heights.

step determines the maximum useful area of the cathode and the electrode angle determines the beam envelope.

DISCUSSION

The measurements and calculations presented here have centered on improving the operational lifetime of the polarized electron source at the Jefferson Lab. The operation of semiconductor photocathode guns with high average current present difficulties not normally encountered for low duty factor guns. For example, at the SLC the most critical factor (particularly for high polarization samples) is actually not the lifetime, but maintaining the peak quantum efficiency necessary to reach high peak currents [2]. At Jefferson Lab, QE is not as important due to the large range of available laser power and the low peak current requirements, but the lifetime is of paramount importance to maintain high accelerator availability.

Ion backbombardment (due to ionization of residual gas in the anode-cathode region) has been shown to be the rate-limiting factor in determining the lifetime. The introduction of high speed pumping close to the cathode and careful electron optical design have reduced the effects of ion backbombardment to tolerable levels and has made multi-hundred hour operational lifetimes possible. In addition, all of these results were obtained without the use of a complicated load lock chamber.

The actual crystal damage that causes the reduction in quantum efficiency is known to depend on vacuum properties, ion energy, electron optics, and crystal properties. There a several important related issues that may effect the operation of future guns planned for use in colliders or as FEL drivers [13]. For example, due to the range of ions as a function of energy, going to higher voltage guns may not cause increased damage since the range is deeper than the characteristic absorption depth for light. Also, the damage in samples with thin active layers compared to bulk samples (such as strained layer and quantum well structures) may be less for the same reasons.

The higher energy ions may effect the underlying crystal, though, especially for complicated quantum well structures [14].

In conclusion, recent improvements to the Jefferson Lab polarized electron source have led to significant increases in the operational lifetime while delivering high average currents. The understanding of the mechanisms involved has implications for future photocathode gun design and efforts are underway to model the cathode damage quantitatively.

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