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Experimental Studies of the Charge Limit Phenomenon in NEA GaAs Photocathodes*

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Abstract

Negative electron affinity GaAs photocathodes have been in continuous use at SLAC for generating polarized electron beams since early 1992. If the quantum efficiency of a GaAs cathode is below a critical value, the maximum photoemitted charge with photons of energies close to the band gap in a 2-ns pulse is found to be limited by the intrinsic properties of the cathode instead of by the space charge limit. We have studied this novel charge limit phenomenon in a variety of GaAs photocathodes of different structures and doping densities. We find that the charge limit is strongly dependent on the cathode's quantum efficiency and the extraction electric field, and to a lesser degree on the excitation laser wavelength. In addition, we show that the temporal behavior of the charge limit depends critically on the doping density.

1 INTRODUCTION

Polarized electrons generated by photoemission from negative electron affinity (NEA) GaAs cathodes with circularly polarized light have been in continuous use for high energy physics programs at SLAC since the spring of 1992 [1,2]. The demand for the highest possible polarization of the electron beam dictates that the energy of the excitation photons must be very close to the band gap energy of the cathode material. Operating under such a condition revealed a new phenomenon in the physics of photoemission from NEA semiconductor cathodes — if the quantum efficiency (QE) of the cathode is below a critical value the total charge extractable from a cathode within a short pulse, on the order of a few nanoseconds, saturates to a limit that is less than what the space charge limit permits [3,4]. This novel charge saturation phenomenon is referred to as the charge limit. Since the SLC requirement for beam intensity is very high, as it is for future linear colliders, the charge limit effect imposes a significant constraint on the usability of NEA photocathodes. We report in this paper a systematic study on the charge limit effect.

2 EXPERIMENTAL

The photocathodes used for the study were those of thin (ranging in thickness from 100 nm to 300 nm), strained GaAs capable of producing high polarization (>60%) electrons. The conclusions of this study are, however, general and applicable to all other types of GaAs-based photocathodes. The experiments were conducted by using the Gun Test Facility at SLAC, which consists of a 20-mm cathode aperture diode gun [5] coupled with a loadlock system [5], two pulsed Ti:Sapphire lasers [5], and an electron beam line terminating into a Faraday cup. To simulate the SLC configuration, one Ti:Sapphire laser was always tuned to a wavelength close to the band gap threshold of the cathode material under study appropriate for producing a high-polarization production beam, whereas the other had a fixed wavelength of about 775 nm for producing a non-polarized scavenger beam. Both lasers had a Gaussian like pulse shape with a pulse width (full width at half maximum) of about 2 ns. Their spot sizes were adjusted to >20 mm at the cathode so that full illumination is ensured. An 833 nm low power cw diode laser was used for QE measurements with a spot size of 14 mm centered on the cathode. Here QE is defined as the linear photoemission response of a cathode to low power light illumination. Specifically, it is the number of photoemitted electrons normalized by the number of incident photons *prior to* entering the gun vacuum. Unless otherwise stated, the cathode was always negatively biased at 120 kV and maintained at a temperature close to 0 °C. The cathodes were prepared following well established procedures that include heat cleaning to 600 °C for one hour followed by activation with Cs and NF_3 to achieve NEA. The vacuum level in the gun was on the order of 1×10^{-11} Torr.

3 RESULTS AND DISCUSSION

A typical saturation plot showing the charge limit effect is displayed in Figure 1. For this measurement, a 300 nm $5\times10^{18}/cm^{-3}$ Zn-doped strained GaAs cathode was used, and the laser had a pulse width of 1.8 ns and a wavelength of 865 nm, corresponding to the cathode's band gap threshold. The QE of the cathode was 0.38% measured at 833 nm. The maximum extracted charge of 3.5×10^{10} electrons is significantly less than that of the space charge limited case, which is in excess of 16×10^{10} electrons. Representative temporal profiles of the charge pulses measured with a fast gap monitor at laser pulse energies spanning the linear response and heavily saturated regions are also shown in Figure 1. Several important characteristics of the charge limit phenomenon are readily recognizable from this figure. (i) Once the photoemission is charge limited, further increase in the laser pulse energy leads to a monotonic decrease in the photo-emitted charge. (ii) With increasing laser pulse energy in the charge limited region, the charge pulse peaks at an increasingly earlier time and shrinks in width as a result of suppressed emission in the later portion of the pulse. (iii) In the charge limit region, the peak current of the charge pulse remains nearly the same but below the space charge limit for varying laser pulse energies. Thus, it is the premature current saturation, i.e., in the sense that it is below the space charge limit, and the suppression of the later portion of the charge pulse that causes the observed charge limit effect.

Similar charge limit behaviors were observed with the 775 nm Ti:Sapphire pulsed laser, but with a higher peak current than that of the corresponding 865 nm charge limit. The disparity between the charge limits measured at 865 nm and

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775 nm depends inversely on the QE, varying from a few percent at the maximum QE to nearly 50% at the lowest measured QE of 0.05% [6]. Such a dependence on the wavelength suggests the increasing importance of hot electrons to photoemission as the surface NEA condition deteriorates. Our measurements also demonstrated that over the range in which the cathode's QE changes by an order of magnitude, the charge limit varies proportionally with the QE, while the laser pulse energy for the onset of charge limit remains unchanged [3,6].

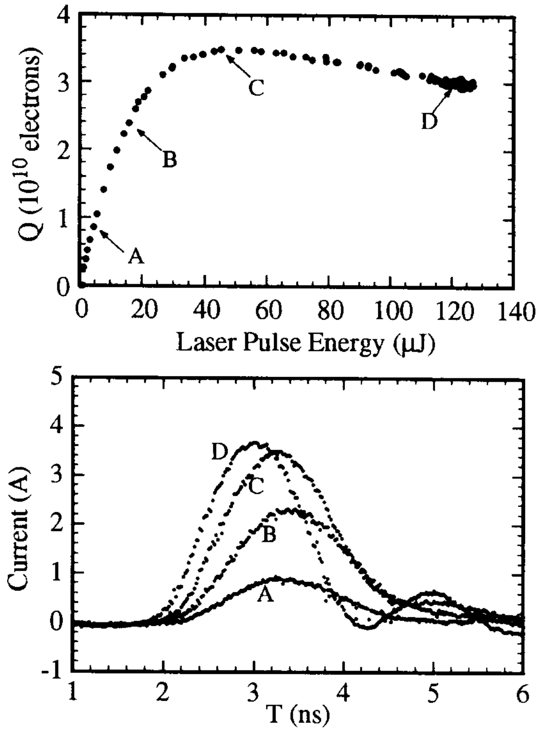

Figure 1: Photoemitted charge versus laser pulse energy (upper panel) and representative charge pulse shapes (lower panel) at several laser pulse energies.

The suppression of the later portion of the charge pulse in the charge limit region suggests that as a large number of electrons are excited from the valence band into the conduction band under intense light illumination , the escape probability of the excited electrons is decreased. This points to an increase in the surface work function. Such a work function increase is most likely caused by the so-called photovoltaic effect. As only a fraction of the electrons arriving at the surface successfully escape, there will be a large build-up of electrons at the surface under intense light illumination. The electrons discharge the positively charged surface and reduce the band bending in the surface region. Consequently, the work function is effectively increased, leading to suppressed emission of later arriving electrons, and therefore, the observed charge limit effect. Herrera and Spicer have modeled the charge limit phenomenon based on the photovoltaic effect [7].

In order to better understand the properties of the charge limit phenomenon and its impact on the performance of the polarized electron source, as accelerators often require closely spaced (in time) charge pulses for their high energy physics experiments, it is important to examine the interpulse effect. Figure 2 shows the effect of the first pulse on the charge in the second pulse as a function of time separation between them for the same cathode discussed previously. The first pulse is pumped by the 865 nm laser and the second one by the 775 nm laser, both being charge limited. The cathode had a QE of 0.79%. It is clearly seen that the presence of the first pulse has a strong negative effect on the charge in the second pulse. As the time separation increases, the peak current in the second charge pulse increases monotonically while its pulse shape remains unchanged. The time scale for the decay of the interpulse effect is on the order of hundreds of nanoseconds, but its form is not a simple exponential.

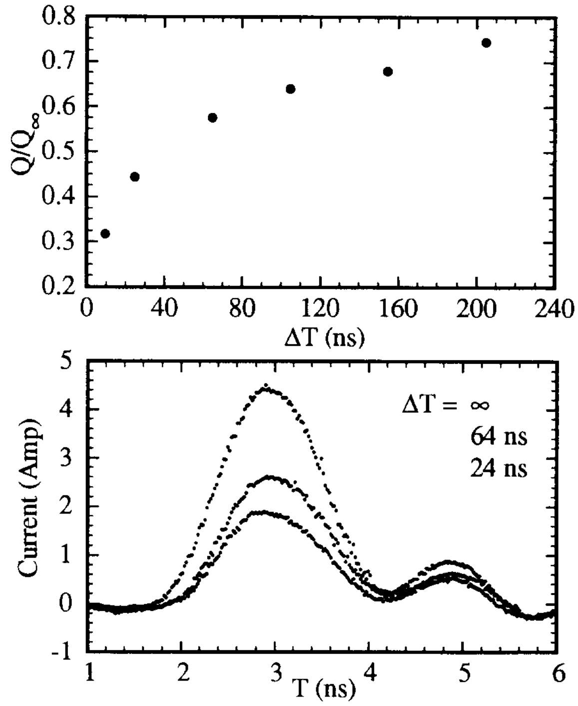

Figure 2: Normalized charge in the second pulse as a function of time sepration from the first pulse (upper panel) and pulse forms of the second charge pulse (lower panel).

Further investigation into the interpulse effect yielded the following findings [6]. (i) The higher the energy of the first laser pulse is, the greater its effect on the second pulse. (ii) The longer the wavelength of the second laser pulse is (or the closer the excitation photon energy is to the band gap energy), the greater the effect the first pulse has on the second one. (iii) The lower the charge limit is, the stronger the interpulse effect. (iv) The time constant that characterizes the decay of the interpulse effect depends critically on the doping density of the cathode. This last characteristic is demonstrated in Figure 3, in which the interpulse effects for two 300 nm strained GaAs cathodes with different Zn doping densities, $5\times10^{18}/cm^{-3}$ and $2\times10^{19}/cm^{-3}$, respectively, are shown. For the more highly doped sample, the interpulse effect is largely diminished for a time separation of 30 ns or larger. In sharp contrast to this behavior, however, the interpulse effect persists to beyond several hundreds of nanoseconds in the sample of lower doping.

In the photovoltaic model, the electrons trapped at the surface are removed by combining with holes from the bulk [7]. These holes may arrive at the surface via two channels, i.e., tunneling through the surface barrier quantum mechanically or overcoming the surface barrier with thermal fluctuations. For cathodes with sufficiently high doping, such as the ones under study, the former is the dominant mechanism. Thus, the removal rate of the surface electrons is determined by the tunneling probability, which is critically dependent on the surface barrier width, i.e., the width of the surface band bending region. As this width is solely determined by the doping density, the strong dependence of the interpulse effect on the doping density is thus expected. In fact, decay time constants as long as 25 sec have been reported for the surface photovoltaic effect in GaAs materials with doping densities of $1\times10^{17}/\text{cm}^{-3}$ or less [8].

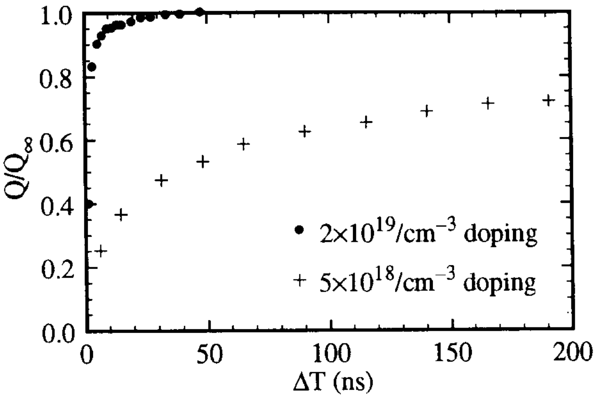

Figure 3: Normalized charge in the second pulse (775 nm) as a function of time separation from the first pulse (865 nm) for two 300 nm strained GaAs cathodes of different dopant densities.

Finally, we show in Figure 4 that the charge limit depends almost linearly on the cathode bias. The data were obtained from the aforementioned higher doping 300 nm strained GaAs cathode with a QE of 0.46% measured at 833 nm. It should be emphasized that for all of the bias settings the measured charge limit is below the projected space charge limit. Thus, the data truly represent the bias dependence of the charge limit. While the charge limit scales with the QE for a fixed cathode bias, its dependence on the cathode bias bears no resemblance to the Schottky effect induced bias dependence of the QE [4,6]. This difference suggests that the extraction field has an added effect on the charge limit.

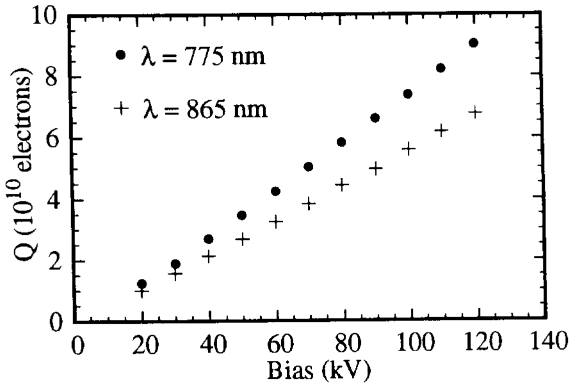

Figure 4: Charge limit versus cathode bias for two laser wavelengths.

4 CONCLUSIONS

The charge limit effect is characterized by premature current saturation and suppressed photoemission in the later portion of the pulse. These two characteristics are intimately related because there would have been no premature current saturation, i.e., the current will always saturate to the space charge limit, if it were not for the suppressed emission of the later arriving electrons. The time constant for the decay of the interpulse effect to decay depends very sensitively on the doping density of the cathode material. Qualitatively, all of the experimentally observed properties of the charge limit phenomenon can be explained within the framework of the photovoltaic effect. The strong dependence of the charge limit on the cathode bias points to the advantage of operating the electron source at the highest possible bias. For future accelerators that require long trains of high intensity beam pulses, one may need to use highly doped cathodes because of their reduced interpulse effect, but with a price, i.e., high doping has an adverse effect on the polarization.

The significance of the charge limit effect for the SLC is that it sets a lower limit on the cathode's QE below which the source fails to meet the SLC intensity requirement. Thus, the cathode must be periodically revived, which involves applying a small amount of cesium on its surface. At SLAC, this action is remote-controlled and takes about 20 minutes during which the accelerator is idling and hence translates into machine down time. However, cesiation cycles on the order of 1 week have been routinely achieved, rendering the source down time almost invisible to the SLC operation.

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