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Study of Non-Linear Photoemission Effects in III-V Semiconductors*

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Abstract

Our experience at SLAC with photoemission-based polarized electron sources has shown that charge limit is an important phenomenon that may significantly limit the performance of a photocathode for applications requiring high intensity electron beams. In the process of developing high performance photocathodes for the ongoing and future SLC high energy physics programs, we have studied the various aspects of the charge limit phenomenon. We find that the charge limit effect arises as a result of non-linear response of a photocathode to high intensity light illumination. The size of the charge limit not only depends on the quantum efficiency of the cathode but also depends critically on the extraction electric field. In addition, we report the observation of charge oversaturation when the intensity of the incident light becomes too large.

I. INTRODUCTION

Polarized electron beams have been in continuous use for the SLC high energy physics program at SLAC since the spring of 1992 [1,2]. The polarized electrons are generated by the Polarized Electron Source (PES) consisting of an electron gun with a GaAs-based photocathode and a laser operated near the cathode band gap. In addition to the requirement of high polarization, the SLC program also demands high beam intensities, i.e., two 2 ns electron bunches separated by 60 ns with up to 10^{11} electrons in each. The gun is operated at 120 kV so that the amount of charge extractable in the space charge limit is about 1.2×10^{11} electrons per bunch for a fully illuminated photocathode (14 mm diameter), which is well above the desired intensity. If a photocathode responds linearly to the excitation light intensity, then, the amount of photoemitted charge will increase proportionally with the light intensity until the space charge limit is reached. In contrast to this expectation, earlier studies [3] indicated that, when the quantum efficiency (QE, defined as the ratio of the number of emitted electrons over the number of incident photons) of the cathode drops below a certain level, the total amount of charge extractable within 2 ns from a fully illuminated cathode saturates to a value that is smaller than the space-charge limited value, a phenomenon becoming known as charge limit (CL). We report in this paper a more detailed study of this nonlinear effect and other important properties in a variety of III-V semiconductor photocathodes.

II. EXPERIMENTAL

All of the experiments were performed by using the Gun Test Facility at SLAC which is essentially a duplicate of the first few meters of the SLC injector. The facility consists of a polarized electron gun with a loadlock system for easy cathode change [4], a YAG-pumped pulsed Ti:Sapphire laser tunable between 750 nm and 870 nm [5], and an electron beam line with a beam position monitor, a fast gap monitor and a Faraday cup. Very high vacuum is maintained in the gun by means of nonevaporative getter pumping as well as ion pumping. A residual gas analyzer (RGA) is used to monitor the gun vacuum. During normal operation, the total pressure in the gun is about 1×10^{-11} Torr and the CO level is about 1×10^{-12} Torr. A large number of III-V semiconductor photocathodes were studied, including 0.3 μ strained lattice (high polarization) $GaAs/GaAs_{0.76}P_{0.24}$, 0.3 μ, 1 μ, and bulk GaAs, and 0.3 μ $Al_{0.12}Ga_{0.88}As$, where the thickness refers to the active layer, all doped with either Be or Zn to a concentration of 5×10^{18} to 2×10^{19} /cm^3. The cathodes are activated by first heating to 610 °C for one hour, then applying Cs until the photocurrent peaks, and followed by codeposition of Cs and NF_3. Two continuous wave diode lasers of wavelengths 750 nm and 833 nm operated at low power (< 1 mJ) were used for QE measurements. Unless otherwise stated, the cathode temperature was always kept at 0 °C. All of the data presented below are obtained from the 0.3 μ strained GaAs cathode, whose results are qualitatively representative of those of the other cathodes.

III. RESULTS AND DISCUSSION

Figure 1 shows the charge versus laser pulse energy data, or saturation curve, for the 0.3 μ strained GaAs cathode. The Ti:Sapphire laser is tuned to a wavelength of 850 nm for the measurement. The QE is 1.51% and .57% at 750 nm and 833 nm, respectively, measured with the laser spot fully illuminating the cathode area. The difference in the QE

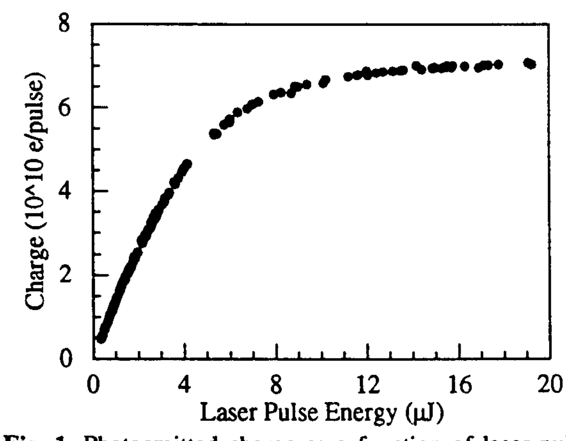

Fig. 1. Photoemitted charge as a function of laser pulse energy at a wavelength of 850 nm.

measured at the two wavelengths can primarily be attributed to the different number of photons actually absorbed by the 0.3 μ thick cathode for an equal number of incident photons at the two wavelengths. From the figure it is seen clearly that for low laser intensities the amount of emitted charge per pulse is

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linearly proportional to the laser pulse energy. However, the dependence quickly becomes nonlinear for higher energies and the amount of emitted charge eventually saturates to a limit of 7×10^{10} electrons/pulse. This behavior is consistent with the results reported in Reference [3]. As the QE drops with time, the charge limit decreases almost proportionally.

The nature of the charge limit is more clearly elucidated in the time resolved electron intensity measurement with the gap monitor. Two temporal profiles of the electron bunch with low and high intensity laser illumination, corresponding to non-charge-limited and charge-limited cases, respectively, are shown in Figure 2. At low laser energy, the electron pulse shape is symmetric and closely resembles that of the laser pulse, indicating that the cathode response to the laser illumination is approximately linear. At the high laser energy when the charge limit is reached, the electron pulse shape becomes asymmetric and peaks at a significantly earlier time than the light pulse. This behavior is very different from the space charge limit manifested by a flat-topped symmetric pulse with the flat top amplitude determined by the space charge limit effect. For our gun operated at 120 kV, the space charge limit is about 10% higher than the peak in the charge limit pulse shown in Figure 2.

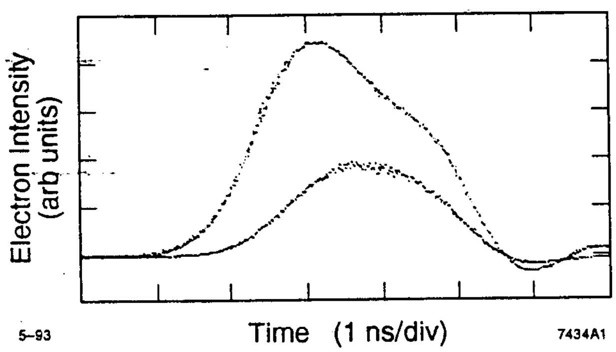

Fig. 2. Charge pulse shapes for incident laser pulse energies at 30 μJ (top trace) and 3 μJ (lower trace), showing charge limit and linear response behaviors, respectively. The laser wavelength is at 850 nm.

The decreased photoemission in the later part of the pulse as revealed by the time profile in Figure 2 is characteristic of the charge limit effect. In the deep charge limit regime, the suppression of photoemission after the electron pulse peaks may be so strong that the electron pulse becomes significantly shorter than the light pulse. These results suggest that as a large number of electrons are excited from the valence band into the conduction band in the cathode, the work function at the cathode surface increases and reduces the escape probability of the excited electrons. Several models have been proposed to account for the induced work function increase [6-8]. Although at present it is unclear which model is correct — and it is possible that more than one mechanism may be responsible— the photovoltaic effect [9] does appear to be the primary cause for the charge limit effect.

To further explore the properties of the charge limit, we studied its dependence on the gun high voltage The data shown in Figure 3 demonstrate that the charge limit is strongly dependent on the high voltage, although less so than the $V^{3/2}$ dependence for space charge limit. The almost linear relation between the charge limit and the high voltage may be coincidental. However, it is clear that the strong dependence cannot be explained by the Schottky barrier lowering effect [10], which, as shown below, models very well the voltage dependence of QE measured at low laser power (i.e., in the linear response regime).

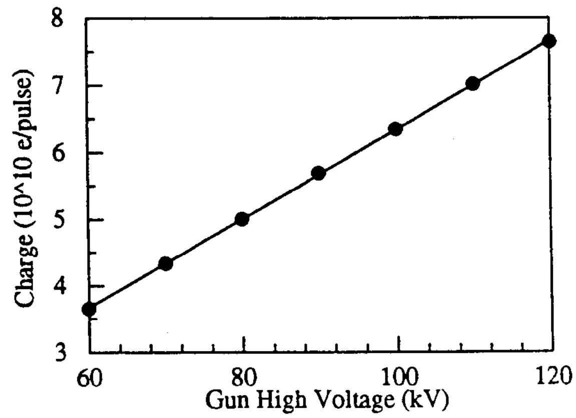

Fig. 3. Charge limit as a function of gun high voltage measured with a 30 μJ laser pulse at 850 nm.

Figure 4 shows two sets of data in the form of ln(QE) versus $E^{1/2}$ (the square root of the extraction electric field at the cathode surface) for two excitation wavelengths [10]. Both can be satisfactorily fit to a linear relation, establishing the validity of the following expression:

$$QE=(QE)_0\times\exp(\beta E^{1/2}), \qquad (1)$$

where β is the slope of the linear fit. The reduction in the work function due to Schottky effect is proportional to $E^{1/2}$ [11].

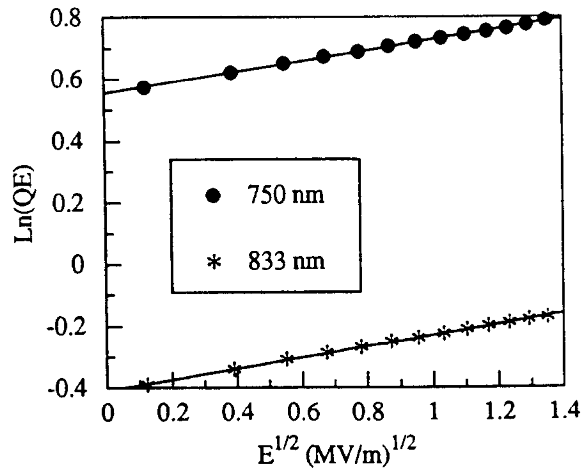

Fig. 4. Quantum efficiencies measured at 750 nm and 833 nm, respectively, versus the extraction electric field. The lines are the best fits to the data.

Therefore, equation (1) demonstrates that the excited electrons can be characterized by an effective temperature when reaching the cathode surface [12]. For the 750 nm and 833 nm excitation photons, we find the effective temperatures to be 201 meV and 193 meV, respectively. The fact that the effective temperatures for electrons excited by the 750 nm and

833 nm photons are almost the same shows that the excited electrons undergo rapid thermalization to the conduction band minimum, i.e., the Γ point, via phonon exchanges with the lattice, whose temperature is about 23 meV at 0 °C. The thermalized electrons are then accelerated in the band-bending region and become hotter when reaching the surface. The weak dependence of the effective temperature on the wavelength of the excitation photons may be attributed to the incompletely thermalized electrons.

The rather different voltage dependencies exhibited by the charge limit and QE indicate that QE is not the only important parameter that determines the charge limit, as suggested in reference [3]. In addition to the surface barrier lowering due to Schottky effect, the external field appears to affect the electron extraction efficiency critically.

We now discuss the effect of the laser wavelength on the charge limit. When the excitation wavelength is changed from 760 nm to 865 nm, the charge limit for the 0.3 μ strained GaAs cathode (at –8 °C) is found to decrease by only about 20% while the QE as evaluated from the linear response region in the saturation data decreases by more than an order of magnitude. Meanwhile, the laser pulse energy required for achieving the charge limit increases by more than an order of magnitude. These observations again show that the excited electrons are rapidly thermalized with the lattice and therefore become largely indistinguishable although at the beginning they may have very different kinetic energies depending on the excitation wavelength. Thus, the charge limit is only weakly dependent on the excitation wavelength mainly due to the incompletely thermalized electrons which are expected to be more energetic for higher photon energies. On the other hand, the number of incident photons required to achieve the charge limit strongly depends, as does the QE, on the wavelength because of the strong wavelength dependence of the optical absorption coefficient near the band gap.

Finally, we show in Figure 5 a saturation plot with the laser pulse energy extending well over the level required for achieving the charge limit. It is striking to see that, after reaching a maximum, the photoemitted charge decreases substantially as the laser energy further increases. Temporal

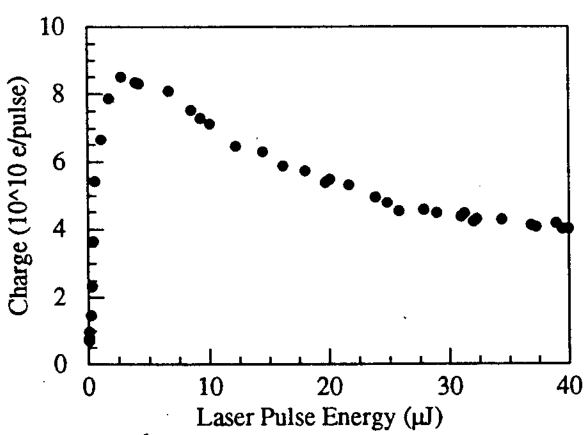

Fig. 5. Photoemitted charge as a function of laser pulse energy (at 760 nm) over an extended energy range.

profiles of the charge pulses measured with the gap monitor at various laser energies show that in the oversaturated regime, i.e., for laser energy greater than 4 μJ, the width of the charge pulse decreases dramatically with increasing laser energy. Although there is also a small, but observable, decrease in the pulse height, it is the decreased pulsewidth that is primarily responsible for the decrease in the emitted charge. The oversaturation phenomenon further illustrates the complicated nature of the non-linear photoemission effect.

IV. CONCLUSIONS

In conclusion, we have studied the various aspects of the charge limit phenomenon. The non-linearity in the photocathode response at high laser intensities arises from the induced increase in the work function. The strong voltage dependence of the charge limit points to the advantage of operating the gun at the highest possible voltage, for high intensity and high polarization electron beams are produced only in very thin cathodes which are almost always operated in the charge limit.

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V. REFERENCES

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[8] H. Tang, *et al.*, "Modeling of the charge limit effect based on the photovoltaic effect", unpublished.

[9] Photovoltaic effect refers to the reduction in the band bending due to the photoexcitation-induced accumulation of charges at the surface of opposite sign (electrons in our case) to that of the original surface charges (positively charged ions in our case) which leads to a reduction in the net amount of surface charges.

[10] The extraction electric field at the cathode is proportional to the gun high voltage. At 120 kV, the extraction field is 1.827 MV/m.

[11] See, for example, S.M. Sze, *Physics of Semiconductor Devices*, p. 250 – 254, John Wiley & Sons, 1981.

[12] The effective temperature T_e is related to ß through the following expression:

$$T_e = (e^3/4\pi\varepsilon_0)^{1/2}/k_B ß,$$

where e is the electron charge, ε_0 the electric permittivity in vacuum, and k_B the Boltzmann constant.