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Physics of High Intensity Nanosecond Electron Source*

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Abstract

A new high-intensity, short-time electron source is now being used at the Stanford Linear Accelerator Center (SLAC). Using a GaAs negative affinity semiconductor in the construction of the cathode, it is possible to fulfill operation requirements such as peak currents of tens of amperes, peak widths of the order of nanoseconds, hundreds of hours of operation stability, and electron spin polarization. The cathode is illuminated with high intensity laser pulses, and photoemitted electrons constitute the yield. Because of the high currents, some nonlinear effects are present. Very noticeable is the so-called Charge Limit (CL) effect, which consists of a limit on the total charge in each pulse—that is, the total bunch charge stops increasing as the light pulse total energy increases. (Details of the characterization of the CL effect and the experimental results are reported by Saez et al. [1], this conference.) In this paper, we explain the mechanism of the CL and how it is caused by the photovoltaic effect. Our treatment is based on the Three–Step model of photoemission. We relate the CL to the characteristics of the surface and bulk of the semiconductor, such as doping, band bending, surface vacuum level, and density of surface states. We also discuss possible ways to prevent the Charge Level effect.

1. Introduction

1.1 Electron source at SLAC

New experiments at the Stanford Linear Accelerator Center (SLAC) involve the measurement of the left–right asymmetry in the production of Z^0 particles, and require a polarized electron source (PES). Operation of the 50 GeV linear collider imposes heavy demands on this PES, such as peak currents of the order of amperes and peak widths of the order of nanoseconds (for example, a bunch charge of $\sim 10^{11}$ electrons). In addition, a high level of stability and reproducibility is required for the hundreds of hours that are necessary for typical experiments.

The PES constructed and used at SLAC is based on photoemission from a GaAs cathode constructed based on negative-affinity technology [2], which is described in the next section. In principle, currents of the order of amperes are obtainable because photoemission from negative-affinity semiconductors can be a very efficient process. Polarization is achieved by using circular polarized laser light and taking advantage of the GaAs band structure [2]. Peak width is controlled by the light impulse width—these sources can be very stable under ultra-high vacuum conditions, even with these high peak currents. Using this technology, it is possible to satisfy the above operational requirements.

1.2 The cathode and operation conditions

The construction of the electron source used at SLAC is based on a negative-affinity technology. Details of the physics of this technology are described by Spicer and Herrera-Gómez in this conference [3]. Briefly, negative affinity cathodes are p-type semi-conductors with a surface treatment to decrease the surface work function. Because of the downwards band bending (see Fig. 1), it is possible to have the surface vacuum level below the conduction band minimum (CBM) in the bulk, producingan effective negative affinity. Figure 1 illustrates some of the characteristics of the SLAC cathode.\

Electron-hole pairs are created all along the active region as the cathode is illuminated. The light is polarized to produce spin polarization. (Description of how the polarization is achieved can be found elsewhere [2].) Some of the photoexcited electrons will diffuse to the surface and escape, constituting the electron yield. The electric field outside the semiconductor, symbolized by the downgrade vacuum level, is large enough to prevent any space charge limited (SCL) effect—SCL occurs when the field produced by the electrons leaving the semiconductor is larger than the external field, preventing any more charge from escaping from the semiconductor. The photoemitted electrons are then focused and sent to the linear accelerator.

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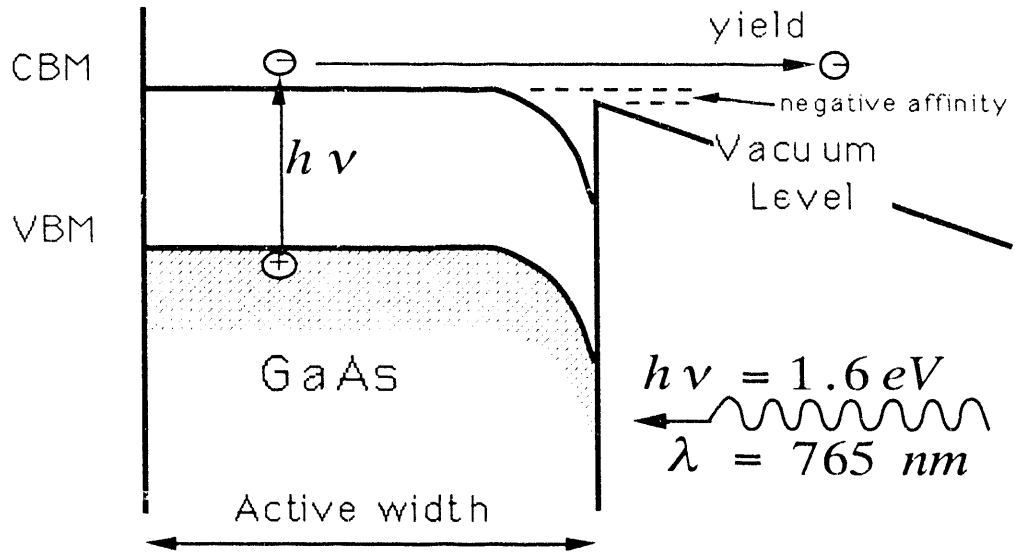

Figure 1. A simplified schematics of the SLAC cathode.

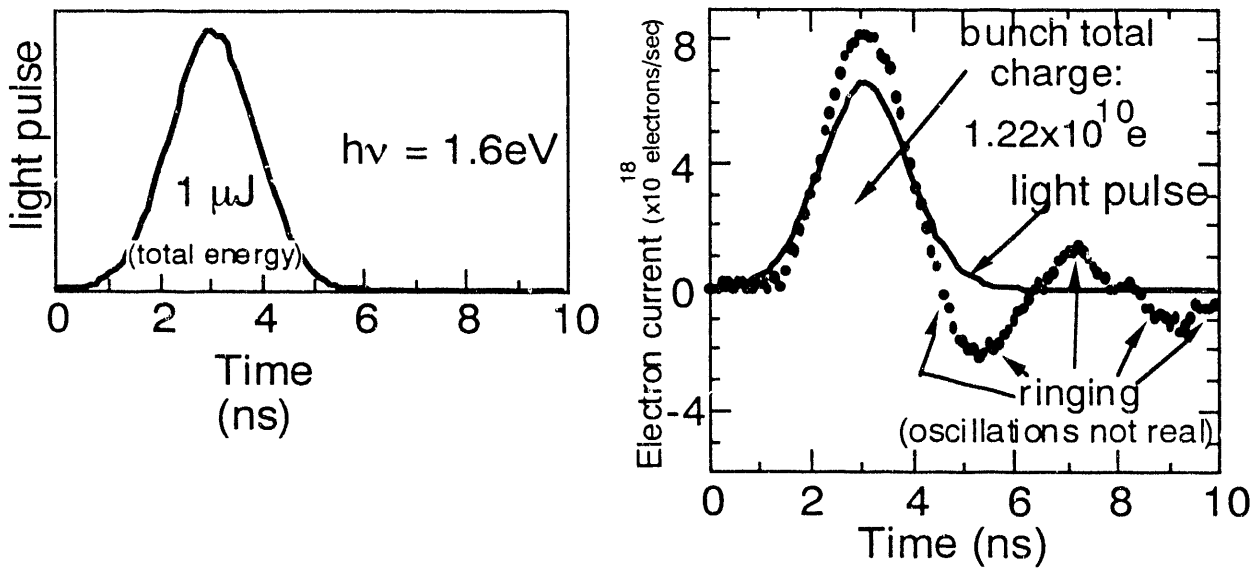

Figure 2. A light pulse with the corresponding electron bunch.

A typical light pulse and electron response are shown in Fig. 2. In this example, the total energy of the light pulse was relatively low (1 μJ), and the total charge emitted by the cathode was 1.22×10^{10} electrons. (Detailed characterization of the SLAC cathode and experimental results are reported by Saez et al. [1], this conference.) The wiggles in the electron response are due to inductance ringing of the current detector, and are not real. We will not show these extra oscillations in the rest of the electron response data.

1.3 Charge Limit effect

The peak current drawn from the cathode is extremely high and, although it does not degrade the cathode due to its pulsed nature, the response of the system is not longer lineal. The integrated charge of each bunch is not proportional to the laser light intensity, showing strong saturation. It should be emphasized that, in some cases, the total charge decreases as the intensity of the light impulse increases. This interesting phenomenon is not very noticeable in Fig. 3, but a downwards slope is found in many cases [1]. Also important is that this charge limit (CL) phenomenon occurs well below the expected limit set by the space charge limited (SCL) effect. Fig. 3 shows the total charge emitted by the cathode as a function of the energy of the light pulse.

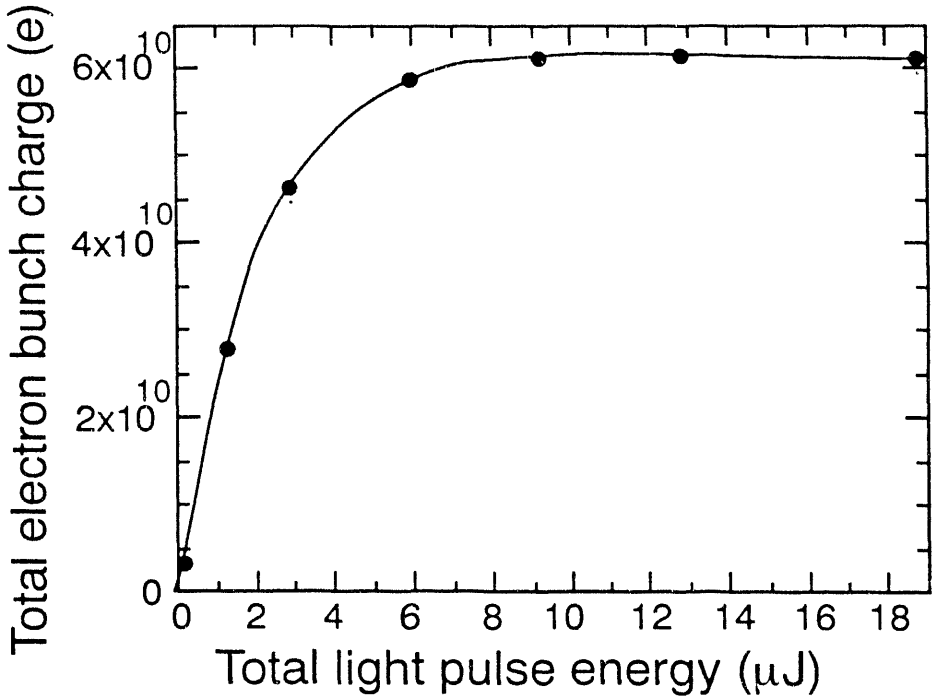

Figure 3. There is a limit on the total amount of electrons obtainable from the cathode. This is the Charge Limit (CL) effect.

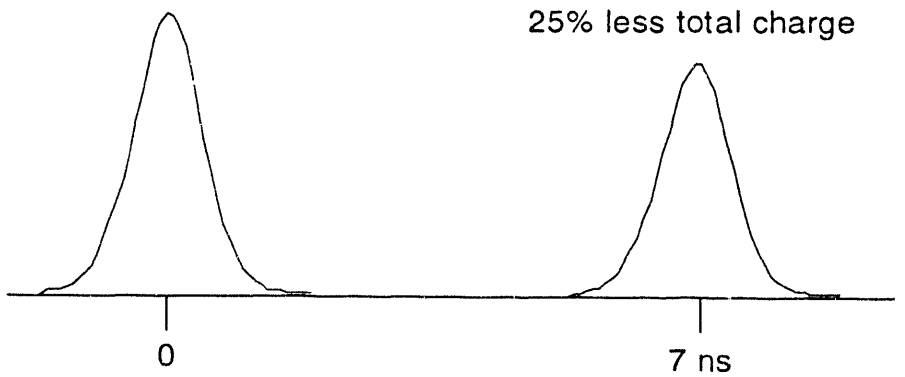

Figure 4. In some cases, it was found that when two bunches are closely spaced in time, the second bunch has less charge [1].

Two more important phenomena related to the CL effect are:

(1) The cathode peak response comes earlier in time as the laser pulse energy increases.

(2) The first of two closely spaced electron bunches affects the second bunch: for identical light pulses, the charge of the second bunch is decreased by the presence of the first. This was observed even for pulse separations of 60 ns for lower semiconductor doping. This effect is also observed at higher doping concentrations ($2 \times 10^{18} cm^{-3}$) with pulse separation of 7 ns, where the charge of the second bunch was reduced by 25%.

Future demands for the delivery of higher peak currents has prompted the study of this CL effect. In this work, we describe the mechanism of the CL, which is based on the photovoltaic effect, and present some preliminary computer modeling of the response of the cathode.

2. THE CHARGE LIMIT MECHANISM

2.1 Electron transport and yield

To discuss the CL mechanism, it is first necessary to briefly describe the overall process (see Fig. 5). The cathode is illuminated with a pulsed laser of photon energy slightly above the band-gap threshold of the semiconductor. The photoexcited electrons in the conduction band are rapidly thermalized by electron-optical phonon scattering, although some of the electrons created near the surface can escape before loosing all their energy.

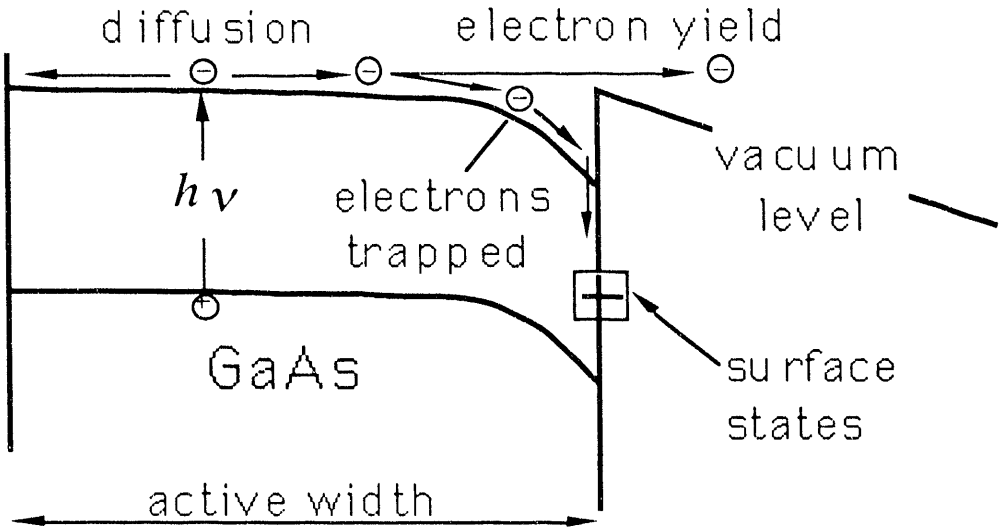

Figure 5. A schematic of the photoemission process in the SLAC cathode.

The electronic transport is approximately described by the diffusion equation [5]:

$$\frac{\partial n(r,t)}{\partial t} = g(r,t) - \frac{n(r,t)}{\tau} + D\,\nabla^2 n(r,t) \quad , \tag{1}$$

where n is the electron concentration and τ the electron lifetime. Because the diffusion coefficient, D, is a slow function of the density of holes [6], it can be considered constant. The extra hole density created by the light pulse is, unless there are extreme conditions, much smaller than the initial hole density. The semiconductor is excited with a light pulse of gaussian shape, with the light emitted from the same side of the electron yield (reflection cathode). The light intensity decreases exponentially as we go deeper into the semiconductor. The generation function, g, is given by

$$g(r,t) = \begin{cases} \alpha I_0 \exp\left(-\left(\dfrac{t-t_0}{\tau_0}\right)^2\right)\exp(-\alpha z) & z < \text{active region} \\ 0 & z \geq \text{active region} \end{cases} , \tag{2}$$

where I_0 is the peak light power, τ_0 and t_0 are the width and the timing of the pulse, and α is the absorption coefficient. Because g is a function of time, everything else is likewise a function of time.

Using these equations and the appropriate boundary conditions, we calculate the rate at which the electrons hit the surface. Some of the electrons escape and constitute the yield. The electric field of the depletion region works as an electron sink for the excited electrons reaching the surface, and those not escaping or bouncing back to the bulk of the semiconductor end up trapped at the surface (J_C in Fig. 10). The surface states—which are responsible for the downwards band bending, and have a net positive charge [7]—act as trapping centers. There is a net flow of excited electrons towards the surface; this current is called photocurrent.

2.2 The photovoltage

In equilibrium, with no illumination, the total surface charge (S_C) exactly cancels the depletion region charge. The size of the band bending (E_B) determines the amount of negative charge in the depletion region, so there is a one-to-one relation between S_C and E_B. Within the "depletion region approximation [7]," the relation is

$$E_B = \frac{S_C^2}{2\varepsilon N_{dop}} , \tag{3}$$

where ε is the dielectric constant and N_{dop} is the doping density. Because S_C is positive, the flow of electrons to the surface decreases the absolute value of S_C, and so of E_B. The change in E_B due to changes in S_C is called photovoltage; specifically ,we have

$$E_B = E_B^0 - PV , \tag{4}$$

where E_B^0 is the band bending in equilibrium and PV is the photovoltage. The surface vacuum level (VL) follows the inverted relation

$$VL = VL_0 + PV . \tag{5}$$

This is illustrated in Fig. 6.

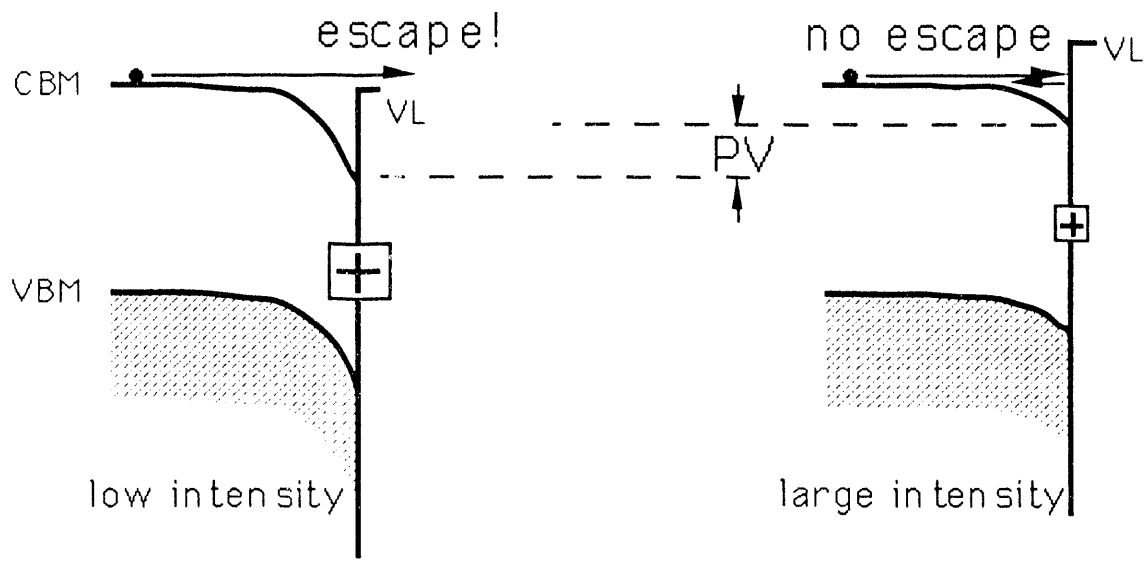

Figure 6. In the low intensity case (left), the surface charge and band bending are large, so VL is low and the electrons can escape easier. With high light intensity (right), there are many electrons falling into the surface states, decreasing the amount of positive charge at the surface, so the band bending decreases. This process raises the vacuum level (VL), so that electrons reaching the surface find a larger barrier to escape.

The increase in VL (Fig. 6) is basically the cause of the CL. The escape probability, P_e, of a electron hitting the surface is a strong function of the electron energy E and of VL. A rough approximation for the electron escape probability can be written

$$P_e = \begin{cases} \text{constant} & E > VL \\ 0 & E \le VL \end{cases} . \tag{6}$$

Although it does not contain the dependence on the bias, it has the basic features of the dependence on E, and can be used as a first approximation. The increase in VL is basically the cause of the saturation (Fig. 6). Figure 7 shows the calculated rise of the vacuum level as the sample is illuminated.

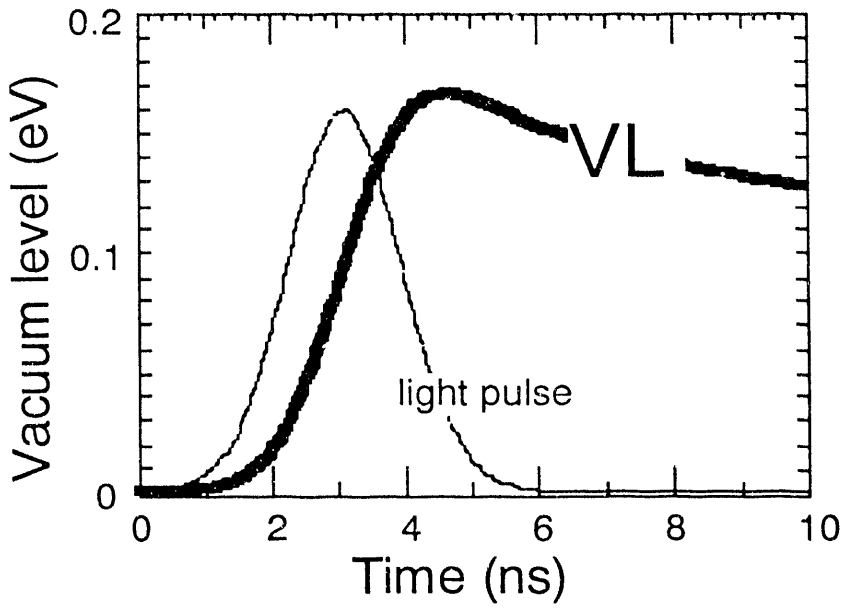

Figure 7. Calculated vacuum level rise when illuminated with a high-intensity light pulse of 65 μJ total energy. After the light is gone, the VL comes back to its original position. This is due to the restoring mechanism that will be explained in the next section. The effect shown in Fig. 4 can be easily explained by noticing that the VL remains up for a period of time.

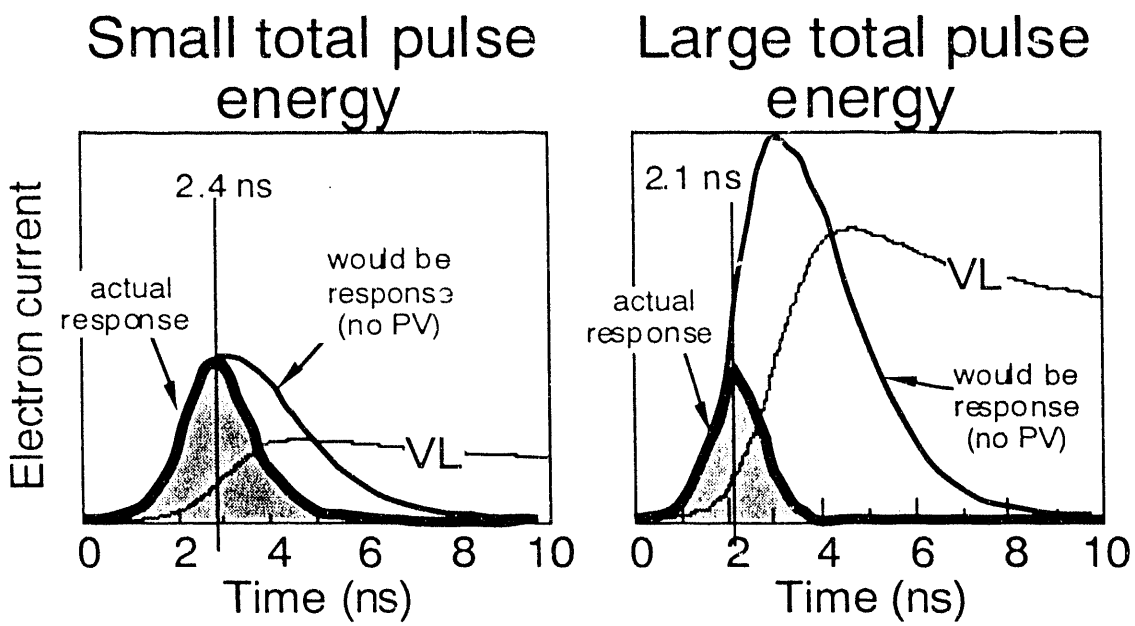

Figure 8. Example of the Charge Limit effect, illustrating how a larger pulse may produce a smaller yield.

As illustrated in Fig. 8, larger light pulses produce larger increases in VL. On the other hand, in the absence of saturation effects, the "would be" response (WBR) is larger for larger pulses. As VL rises, the actual response cannot follow WBR because fewer electrons can escape. With a large VL increase (~ 0.1 eV), the cathode almost completely shuts down. How fast VL rises depends on the rate at which photoexcited electrons reach the surface, which depends on the light intensity. The saturation and decrease of electron yield with increasing light intensity is due to a rapid VL rise, preventing most of the electrons that would have contributed to the yield from escaping.

Notice that the peak of the response comes earlier for the larger pulse. This mechanism is analogous to air coming through a door, as illustrated in Fig. 9.

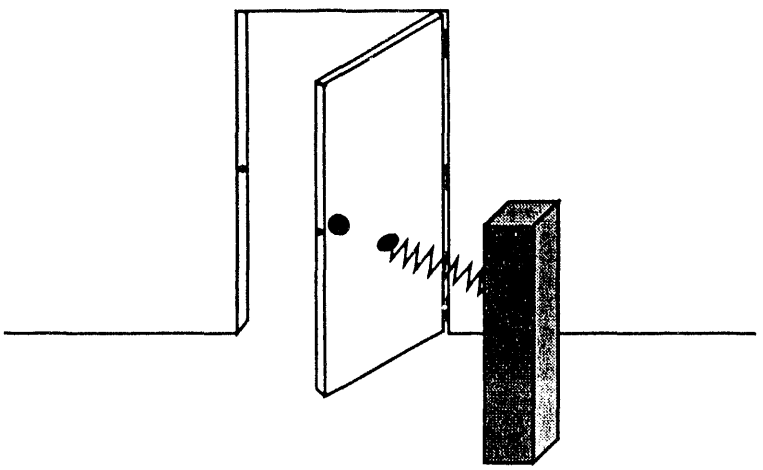

Figure 9. If the wind coming to the door is very strong, it will dominate over the spring, which is trying to keep the door open, so the door will close and only at the beginning will any air make it through. Softer wind may not be able to shut the door, so air will go through the door longer. In this analogy, the wind corresponds to the electrons reaching the surface, the air making it through the door is the electron yield, the door is the vacuum level, and the spring is the restoring mechanism explained in the next section.

2.3 The restoring currents

Electrons reaching the surface is not the whole story; they also have a way to leave the surface and go back to the bulk of the semiconductor. The semiconductor is heavily doped p-type, so there are plenty of holes at the top of the valence band where the electrons trapped at the surface could tunnel and recombine. This is easier to visualize if we talk about holes tunneling into the surface (J_{tunn}). Another less important restoring current is hole thermionic emission (J_{th}) (see Fig. 10).

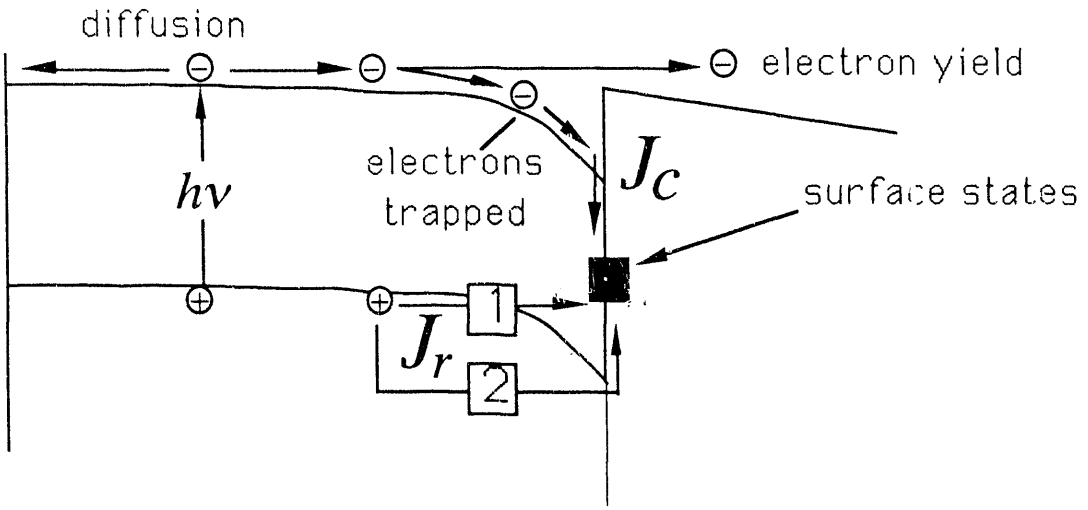

Figure 10. Electrons trapped at the surface of a heavily doped p-type semiconductor can tunnel and recombine. The trajectory mark with "1" is the hole tunneling current (J_{tunn}), and with "2" is the thermionic emission current (J_{th}). The J_C is the current from the photoexcited electrons in the conduction band into the surface, and J_r are the restoring currents.

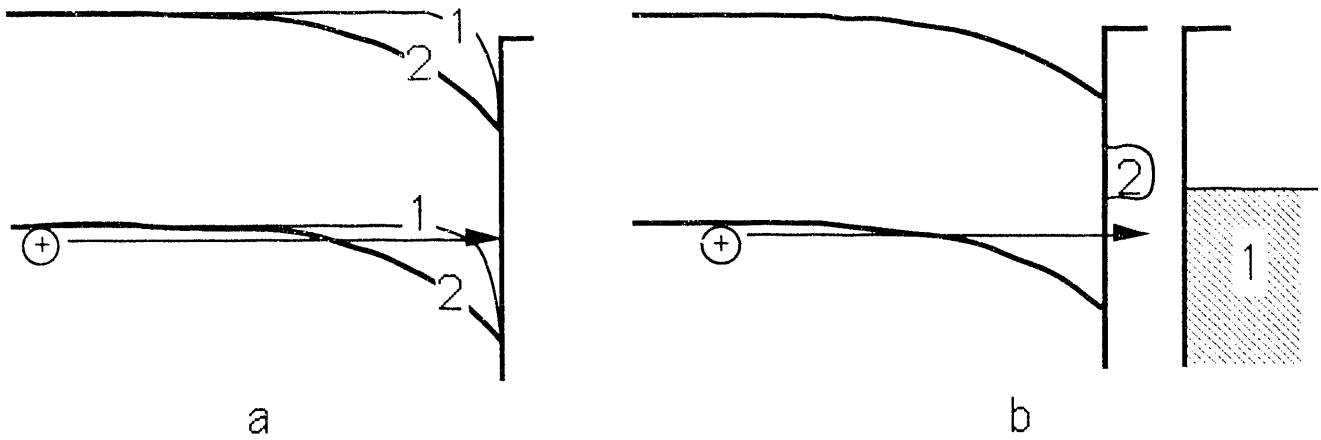

Figure 11. (a) Tunneling is weak at the barrier marked with "2" because the depletion region is large (low doping), and the tunneling probability decreases strongly with the width of the barrier. In contrast, the barrier marked with "1" is thin enough to easily allow tunneling. (b) Another important factor determining the strength of the tunneling current is the density of occupied quantum states at the surface. The surface state density marked with "2" does not have occupied quantum states at the energy of the bulk valence band maximum, so the holes in the valence band have nowhere on the surface to tunnel to. In contrast, a metallic density of states (marked with "1") has a continuum density of occupied quantum states, allowing tunneling.

With photovoltage present, the restoring currents (J_r) are no longer zero, and are in the opposite direction of J_C. The restoring currents drain the extra electrons arriving to the surface by injecting holes. The speed at which these currents restore equilibrium, and their relative importance, depends on the characteristics of the cathode and the amount of photovoltage.

For thermionic emission to be important, the band bending has to be small, a condition that is fulfilled when the photovoltage is large. With high doping, the dominant restoring current is tunneling. The strength of the tunneling current also depends on the distribution density of occupied states at the surface (see Fig. 11).

The rate of change of the surface charge is

$$\frac{d}{dt} S_C = J_r - J_c \quad . \tag{7}$$

If the doping and the density of occupied surface states are high, hole tunneling can prevent the building of any photovoltage, which will prevent the occurrence of the CL effect.

3. Results of the Preliminary Calculations

Fig. 12 shows calculated photovoltage (or VL rise) as a function of time for a light pulse of 65 μJ. It also shows the light pulse, and the experimental and calculated electron response. As can be seen, the maximum of the electron response comes earlier than the light peak.

Fig. 13 compares the electron response to a small and to a large light pulse. The heights have been normalized. Notice that, for the larger pulse, the peak width is smaller and the maximum of the current comes earlier.

Fig. 14 shows three curves of the type shown in Fig. 3. These three curves correspond to different values of the quantum efficiency (QE). The QE is measured at low light intensities, and is intimately related to the initial value of VL, which is related to the level of surface deterioration. For the calculations, no parameter varies except QE, which is given experimentally.

As can be seen in Figs. 12, 13, and 14, even though our model is in a primitive stage, it nicely reproduces the most important characteristics of the data.

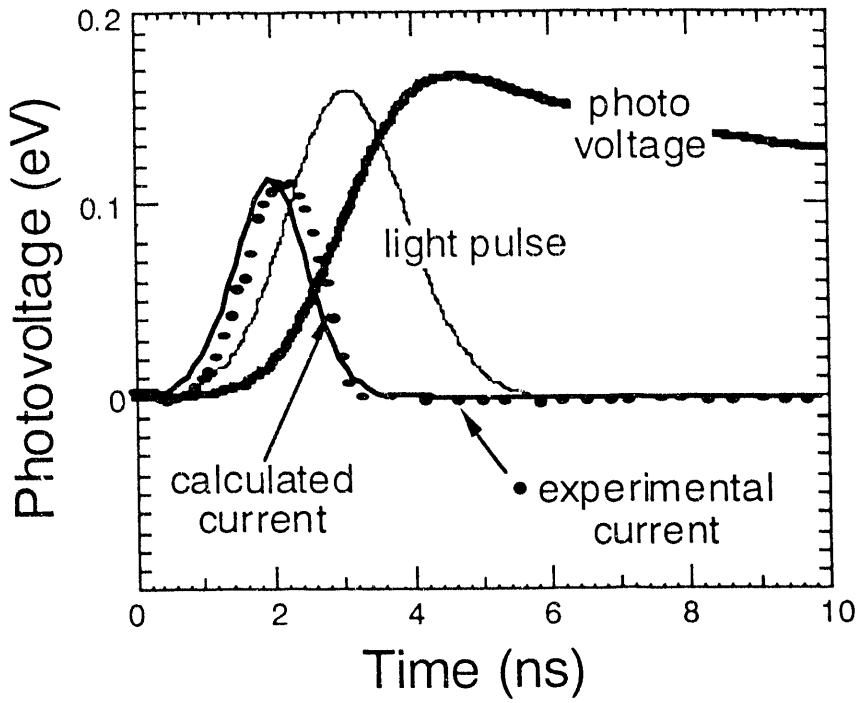

Figure 12. Photovoltage as a function of time. Also shown are the experimental and calculated electron response, as well as the light pulse.

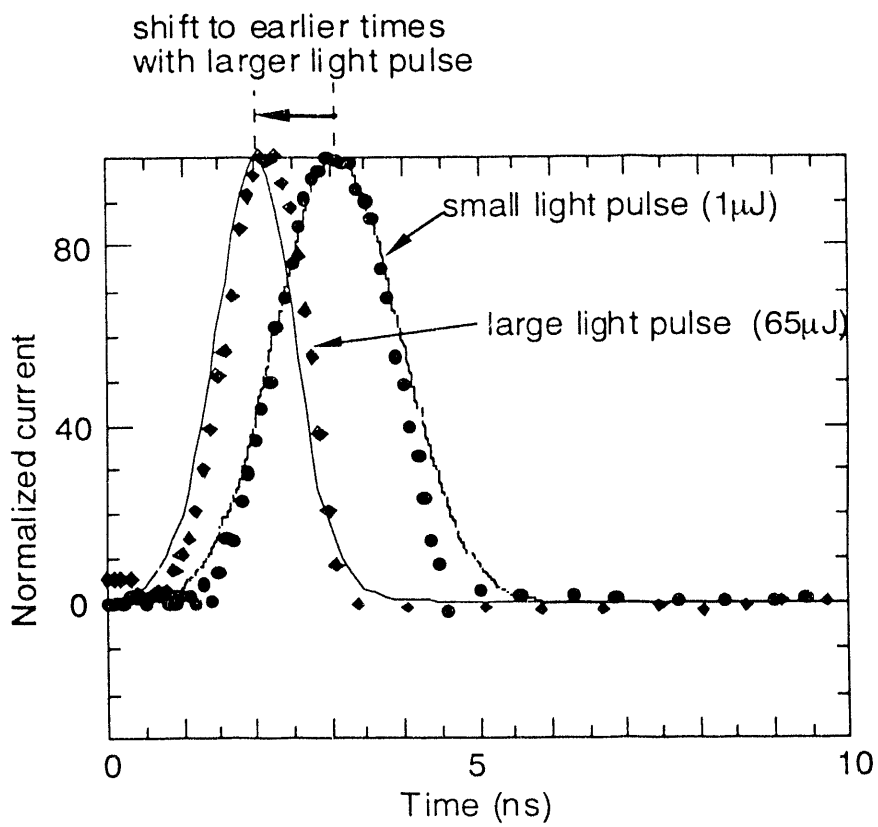

Figure 13. Normalized electron responses for large and small light pulses.

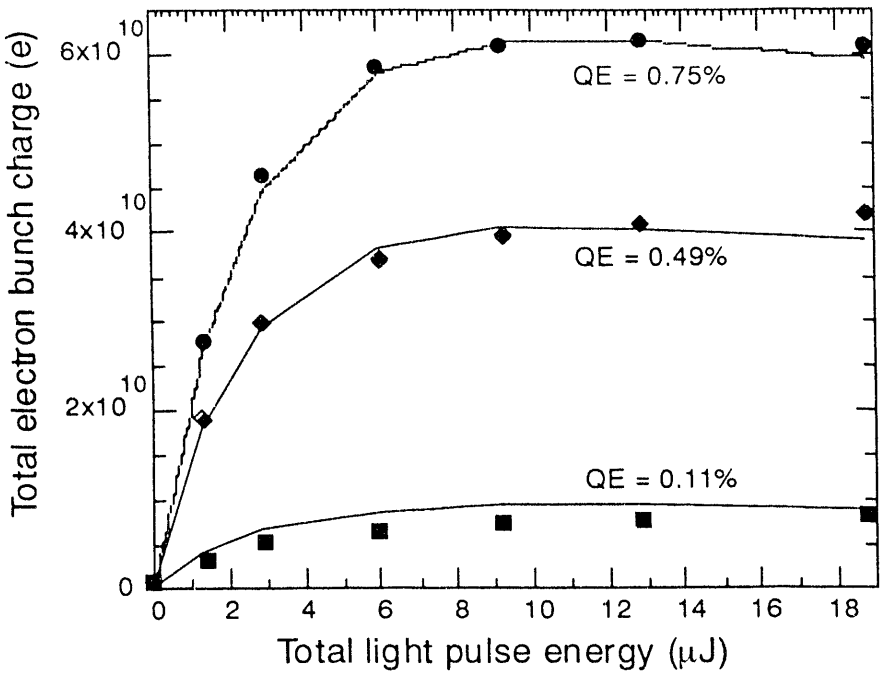

Figure 14. Experimental (dots) versus calculated (lines) total charge versus light intensity.

4. Future Work

Some of the points that need to be addressed to improve calculations are:

(1) Refinement of the model of the escape probability of Eq. 6 to include the bias dependence.

(2) Investigation of the strength of the contribution to the yield from the hot electrons, which are excited near the surface and have not been thermalized by the time they hit the surface (see Fig. 9). Their contribution may be very significant for low QE cathodes. This also introduces the dependence on $h\nu$.

(3) In connection to the last point, we will calculate the relation between the polarization and the rest of the parameters, mainly the thickness of the active layer and the QE. Polarization will be modeled in terms of a depolarization length.

(4) The effect of a discontinuous energy distribution of the surface states, as well as their density, on the tunneling restoring current.

5. Conclusions

The charge limit, or saturation of the electron yield, is due to the photovoltaic effect. A possible way to avoid this problem is by incorporating a metallic layer at the surface. This prevents the formation of a photovoltage by allowing easy tunneling and the drain of the extra charge at the surface. Some experiments testing this possibility are currently underway. The most important characteristics of the electron yield (as the shown in Fig. 3) are already explained by the still not polished present model. The decrease in electron yield with increasing light pulse energies can be easily explained in term of the competition of the photocurrent and the restoring currents. The earlier response with increasing light pulse energy is due to saturation when a large number of electrons are reaching the surface; most of the yield comes at the beginning, when not to many electrons are arriving. This "beginning" is earlier in time for the higher intensity pulses.

This is the first detailed study of high-intensity, short-time electron sources.

6. Acknowledgments

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