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Physics of High-Intensity Nanosecond Electron Source: Charge Limit Phenomenon in GaAs Photocathodes[◊]

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ABSTRACT

The GaAs Negative Electron Affinity (NEA) cathode is being used as a high-intensity, short-time electron source at the Stanford Linear Accelerator Center (SLAC). When the cathode is illuminated with high-intensity laser pulses it draws peak currents that are extremely high, typically of tens of Amperes. 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 pulse in each pulse; that is, the total bunch charge stops increasing as the light pulse total energy increases. The CL effect is directly related to a photovoltage built up in the surface as consequence of the amount of photoelectrons coming from the bulk. We computer model this mechanism and compare our results with experimental data from SLAC. We also study the role of restoring currents in the whole process, which are very important for preventing the CL mechanism. We discuss possible ways to minimize the formation of the surface photovoltage.

1. INTRODUCTION

Polarized electrons generated by photoemission from NEA GaAs photocathodes have been used at the Stanford Linear Accelerator Center (SLAC) since 1992. This cathode fulfills operational 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 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 GaAs. However, operating the photocathode under such conditions produced a new phenomenon in the physics of photoemission from NEA semiconductor cathodes: the total charge extractable from a cathode within a short pulse (on the order of nanoseconds) saturates to a limit that is less than what the space charge limit permits. This effect is called the Charge Limit (CL) effect**.**

When illuminated with high densities of light, the photo-cathode draws extremely high peak currents. Although this 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 impulses increases (over saturation). Other important phenomena related to the CL effect are [1,2]:

- ◊ The charge pulse becomes narrower and peaks at an earlier time as the intensity of incident light increases
- ◊ The phenomenon of oversaturation decreases as the doping level increases
- ◊ 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 bunch.

- There is an upward shift of the laser energy for maximum charge in the second bunch.
- The harder the first pulse is pumped, the greater its effect on the second pulse.
- The longer the wavelength for pumping the second pulse, the greater the effect the first pulse has on the second one.
- The time constant that characterizes the decay of the interpulse effect varies with the doping level; a typical value of this parameter is a 1 μs for a doping level of 5×10^{18} cm^{-3}.

Herrera and Spicer [3] have recently developed a model based on the photovoltage effect for NEAs in order to address this question. We describe here the physics involved in the Charge Limit effect; and how it explains the experimental cathode response. We also describe the methods employed and some successfully fitted experimental curves.

2. The Charge Limit mechanism

2.1 Electron transport and yield

To discuss the Charge Limit (CL) mechanism, it is first necessary to briefly describe the overall process. The cathode is illuminated with a pulsed laser of photon energy slightly above the band gap threshold of the semiconductor (see Fig. 1). 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 losing all their energy.

The diffusion equation describes the electronic transport:

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

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 [4], 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 is given by

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

where I_o is the peak light power, τ_o and t_o 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 in the depletion region works as a sink for the excited electrons reaching the surface, and those not escaping or bouncing back to the bulk are trapped at the surface (J_c in Figure 1). The surface states, which are responsible for the downward band bending, have a net positive charge and act as trapping centers.

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 direct relation between S_c and E_B. Within the *depletion region approximation* [5] 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 Figure 2.

The increase in VL is, basically, the cause of the CL. The escape probability, P_e, of an 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:

$$P_e = \text{constant} \qquad E > VL \tag{6}$$

$$P_e = 0 \qquad E < VL$$

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. 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.

2.3 THE RESTORING CURRENTS

Electrons reaching the surface is not the whole story. They have two ways to leave the surface and go to the back of the semiconductor:

- The cathodes used at SLAC are heavily doped p-type, so that there are plenty of holes at the top of the valence band. The electrons trapped at the surface can tunnel and recombine with these holes. The resultant current has direction opposite to that of J_c, and is called tunneling current (J_{tunn}). This is easier to visualize if we talk about holes tunneling into the surface.
- When the band bending is small, some holes can overcome the barrier and recombine with the electrons trapped at the surface. The resultant current also has direction opposite to that of J_c. It is the hole thermionic current (J_{th})

Both currents, J_{tunn} and J_{th} (see Figure 1), prevent building up of photovoltage, and they are restoring currents. The total restoring current (J_r) can be expressed as,

$$J_r = J_{tunn} + J_{th} \tag{7}$$

With photovoltage present, the restoring current (J_r) is no longer zero, and it drains the extra electrons arriving to the surface by *injecting* holes. The rate at which these currents restore the equilibrium, and their relative importance, depends on the characteristics of the cathode and the amount of photovoltage.

The tunneling current is weak for low doping levels because the depletion region is wide and the tunneling probability decreases strongly with the width of the barrier. Another important factor determining the strength of the tunneling current is the density of occupied states at the surface. When the surface state density does not have occupied quantum states at the energy of the bulk valence band maximum (VBM), the holes in the valence band have nowhere on the surface to tunnel to. However, a metallic density of

states has a continuum density of occupied quantum states allowing tunneling [see Figure 3(B2]). These are extreme cases. For a GaAs cathode, the situation is intermediate between the cases presented in Figure 3. However, we do not know the precise density of surface states, which depend on such factors as surface quality, activation layer, etc., and may change from one cathode to another. In our computer calculations, we introduce a parameter that model this effect—we call this parameter *tunneling factor* (TF) because it works like a weight factor on the current tunneling expression. On the other hand, for thermionic restoring current to be important, the band bending has to be small. This condition is fulfilled when the photovoltage is large.

We are dealing with high doping levels ($>10^{18}$ cm^{-3}); we thus expect that, at the beginning and whenever possible, the most important restoring current will be the tunneling current. As the photovoltaic effect increases, the band-bending width becomes thinner, increasing both the thermionic current and the tunneling current.

The rate of change at the surface charge is

$$\frac{d}{dt}S_c = J_r - J_c \tag{8}$$

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

The whole mechanism is analogous to air coming through a door, as illustrated in Figure 4. 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 closes—it is only at the beginning that any air will make it through the doorway. 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 doorway is the electron yield, the door is the vacuum level, and the spring is the restoring mechanism.

3. RESULTS

We computer modeled this process described at Section 2. As explained there, the CL effect is based on a temporal variation of the vacuum level (VL) due to neutralization of the initial positive charge trapped at the surface states by the photoelectrons coming from the bulk. Figure 5 shows the calculated temporal variation of the PV for two cathodes with different p-doping concentration. The light used was a Gaussian pulse (dotted line Fig. 5A) of 2 ns (FWHM) and 1 μJ (A) and 90 μJ (B). In both cases, we used the same TF. In Case A, the light intensity is low and the cathode doesn't reach its saturation zone. From Eq. 3, the smaller the p-doping level, the smaller the amount of incoming charge necessary for moving the VL. This is the reason the PV increases faster and higher as the p-doping level becomes lower. The rate at which the VL recovers its original value depends on the strength of the restoring currents. In the case of a lower p-doping concentration, 1.5×10^{18} cm^{-3}, the restoring time is much longer. Here, the intensity of the incident light is relatively low and the cathodes are not into the saturation zone. The VL motion is very small, and the difference between the low and high p-doping levels comes mainly from the tunneling current, which is very sensitive to the width of the band bending region—as expected, the higher the doping level, the shorter the restoring time. On the other hand, in Figure 5(B) we see the same curves for high intensity pulses (90 μJ). In this case, the cathodes are working at the saturation zone. The amount of incoming charge is so big that the increase of the PV is independent of the doping level, as is the final PV position. The VL motion is large, and, at the beginning, both restoring currents are present, and the restoring time is practically independent of the p-doping level. Just when the band bending has recovered a large part of its initial value, the tunneling current starts to become more important than thermionic current, so that the restoring time depends on the p-doping level, as it does in the case of a low light level.

Figure 6(A) plots the calculated photovoltage (PV), the *would be* response if the CL mechanism did not exist, and the calculated response for a 300 nm strained GaAs cathode that is Zn-doped to a concentration of 1×10^{19} cm^{-3} and NF_3 activated. The input pulse is a 2 ns FWHM, 40 μJ, 865 nm Gaussian pulse (more details about the experimental setup are reported in Ref. [1]). As the light intensity increases, the number of photoelectrons reaching the surface increases; as a result, the photovoltage also increases. We have two opposite effects: the number of the photoelectrons increases with the intensity of light, but, at the same time, the vacuum level increases as a consequence of the photovoltage effect. The final result is that the photocurrent peaks before the input pulse, and the final response is a narrower and earlier pulse. This is exactly what is observed experimentally. In Figure 6(B,) we see the temporal shift between responses to pulses of different intensities. The solid lines correspond to calculated pulses and the dotted lines correspond to experimental curves.The fitting of these two curves was done using the same parameters, but varying the incident light intensity.

Figure 7 shows the CL effect for the cathode described above, with various escape probabilities. The points represent experimental data and the solid lines the calculations. The parameters used for fitting these curves are the escape probability (EP) and the tunneling factor (TF). The quantum efficiency (QE) was measured experimentally. The low QE values presented here are directly related to the thickness of the sample (only 300 nm), which is shorter than the light absorption depth for the incident wavelength used. The most remarkable result that for *high* escape probability, the thermionic current is the only restoring current present in the CL process (TF = 0). The photocathode p-doping concentration is high (2×10^{19} cm^{-3}), and therefore the potential barrier against holes must be narrow. These are very favorable conditions for tunneling. However, the TF found during the calculations is zero in three of the four cases presented here. This means that the electrons have nowhere to tunnel; i.e., the energy range of the surface

states does not match the valence band minimum energy (Case 1 in Figure 3). On the other hand, for *bad* cathodes (those with low QE) the TF isn't zero, and the restoring current has both thermionic and tunneling components. It seems that low QE is directly related to the increase of the *metallicity* of the activation layer. The restoring rate for low-QE cathodes seems to be higher than those for high-QE cathodes.

Figure 8 shows the calculated PV temporal evolution for a 2×10^{19} cm^{-3} p-doped cathode, for two different TF values, illuminated with a pulse of 80 μJ and 2 ns. Under these conditions, the cathode works at deep saturation zone. It is clear how important the tunneling current is for restoring the VL initial position for samples that are highly doped and working at saturation. The strength of the thermionic current is not enough to quickly neutralize a strong photovoltage effect.

As mentioned in the introduction, another important aspect of the CL mechanism is the memory effect on pulse trains. When the time between two pulses of light is less than the time spent in recovering the original VL position, the integrated current drawn corresponding to the second pulse, Q_2, will be smaller than for the first one. Figure 9 plots the experimental and calculated $Q_2(t)/Q_2(\infty)$ versus time between pulses (t) curves for a 2×10^{19} cm^{-3} Zn-doped 300 nm strained GaAs (100) cathode. The laser wavelengths were 775 nm and 865 nm, the pulse intensity was 35 μJ, and the pulse FWHM was 2 ns. At this intensity the cathode is deep into the charge limit region. The restoring currents spent almost 80 ns in recovering the initial VL position. This time will be very important for experiments where the timing between pulses must be very short. As shown above, the tunneling current, if it exists, is the most important restoring current. For high doping levels, the main obstacle for tunneling is the surface-state density distribution. If we create a high density of surface states at an energy corresponding to the VBM energy, the TF will increase and the restoring times will be shorter.

In order to stress the importance of the surface density of states, we present a case where the surface density of states was more important than the initial value of the VL in determining the quality of the cathode. Figure 10 plots the integrated charge, Q, versus laser-pulse intensity curves corresponding to two different treated cathodes. Both of these GaAs photocathodes consist of a glass window onto which an antireflection coated AlGaAs/GaAs heterostructure has been bonded. The AlGaAs layer is on the order of 0.5 μm thick. The GaAs layer was on the order of 1.5 μm thick. Both of the epitaxially grown layers are Zn doped to an acceptor density of 1×10^{19} cm^3. These cathodes were metallized with an 8 Å Pd layer before activation with Cs and O. Curve A corresponds to the case which has a pure Pd layer just before the activation. Curve B corresponds to the case which has a Pd oxide layer just before the activation. A Pd deposition on the order of 8 Å results in a ~ 95% loss in photoresponse. The QE obtained were 3% for Case A and 4.5% for Case B at 750 nm. Even with a lower QE—that is, a lower initial VL—the cathode with pure metal on the surface draws higher currents and saturates at higher light intensities. This is clear evidence that the tunneling currents are favored by a metallic density of states.

4. CONCLUSIONS

The charge limit, or saturation of the electron yield, is due to the photovoltage effect. The decrease in electron yield with increasing light pulse energies can be explained in terms 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 have reached the surface and the built up photovoltage is small.

When present, the tunneling current is the main restoring mechanism. Our calculations show that the presence of a *metal-like* density of surface states makes the restoration times shorter. This is experimentally supported by a deposition of a thin metal layer, which decreases the cathode's quantum efficiency, and also decreases the restoring time remarkably. As a result, when illuminated with intense pulses of light, the current drawn from a cathode with a metal surface layer is higher than that drawn from a cathode without such a metallic layer, even though its quantum efficiency is smaller.

Acknowledgments

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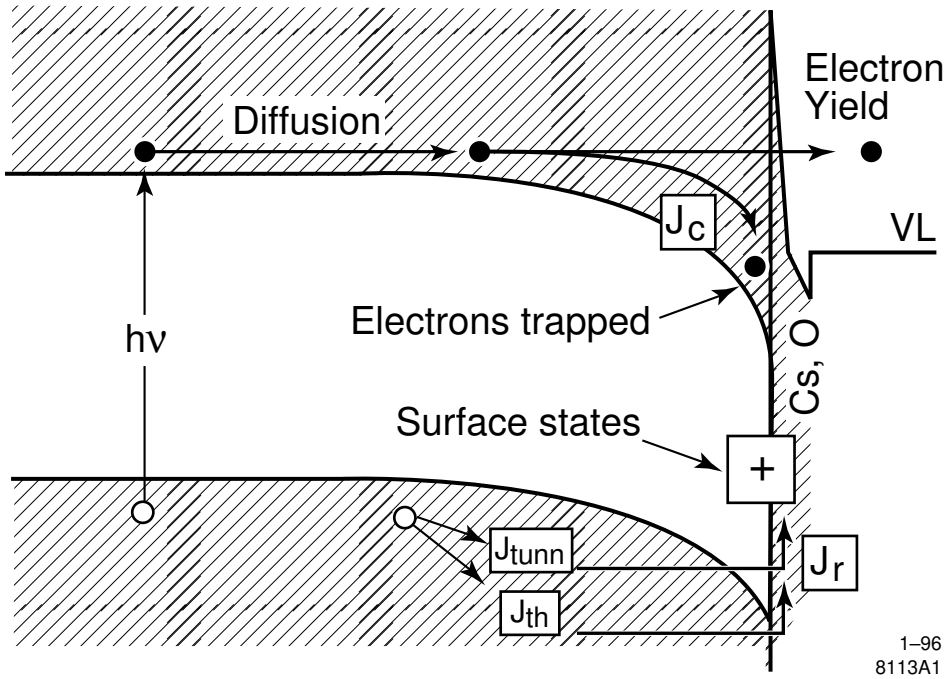

Figure 1. Photoemission process for a NEA cathode. Photoelectrons diffuse to the surface. Some of them escape to the vacuum (yield); the rest are trapped by surface states (J_C). The restoring currents, thermionic (J_{th}), and tunneling (J_{tunn}) neutralize the charge trapped at the surface states.

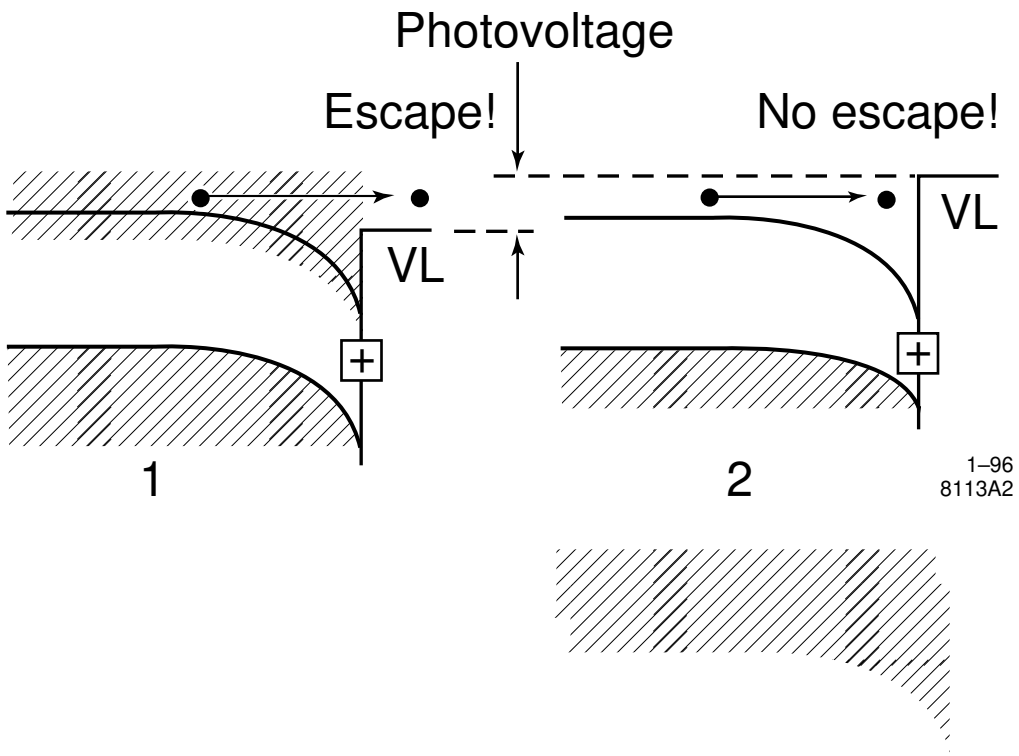

Figure 2. The photovoltage (PV) built up at the surface is responsible for the Charge Limit effect. (1) When illuminated with low intensity light, the surface charge and band bending are large, so Vacuum Level (VL) is low and the electrons can escape easily. (2) When illuminated with high intensity light, there are many electrons *falling* into the surface states, thus decreasing the amount of positive charge at the surface, so that the band bending decreases. This process raises the VL, so that electrons reaching the surface find a larger barrier to escape.

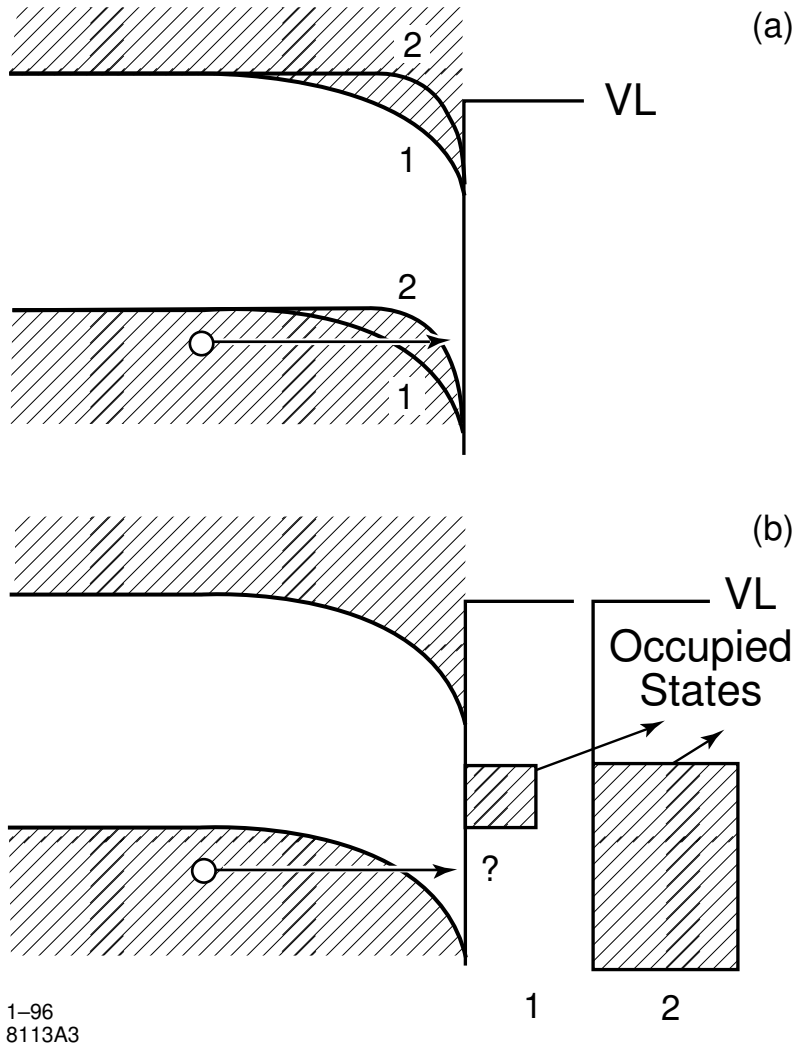

Figure 3. (A) Tunneling is very sensitive to the p-doping concentration. In Case 1, it is weak because the depletion region is wide (low doping). In contrast, barrier 2 is thin enough to easily allow tunneling. (B) Another important factor determining the strength of the tunneling current is the density of occupied states at the surface. The surface state density marked with "1" does not have occupied states at the energy of the bulk valence band maximum, so the holes have nowhere on the surface to tunnel to. For Case 2, the metallic density of states has a continuum density of occupied quantum states, allowing tunneling.

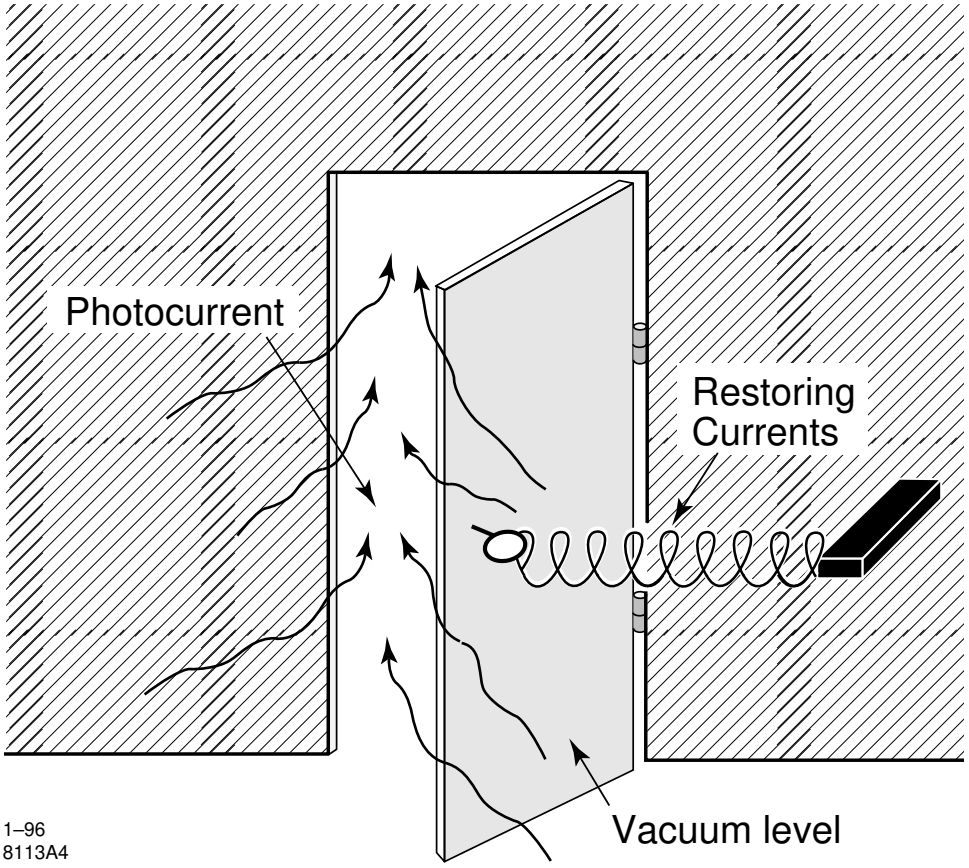

Figure 4. The CL effect is analogous to air coming through a doorway where the door is held tight to the wall with a spring. If the wind coming to the door is very strong, it will dominate over the spring which is trying to keep the door open. So the door will close, and only at the beginning will any 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 doorway is the electron yield, the door is the VL, and the spring represents the restoring currents.

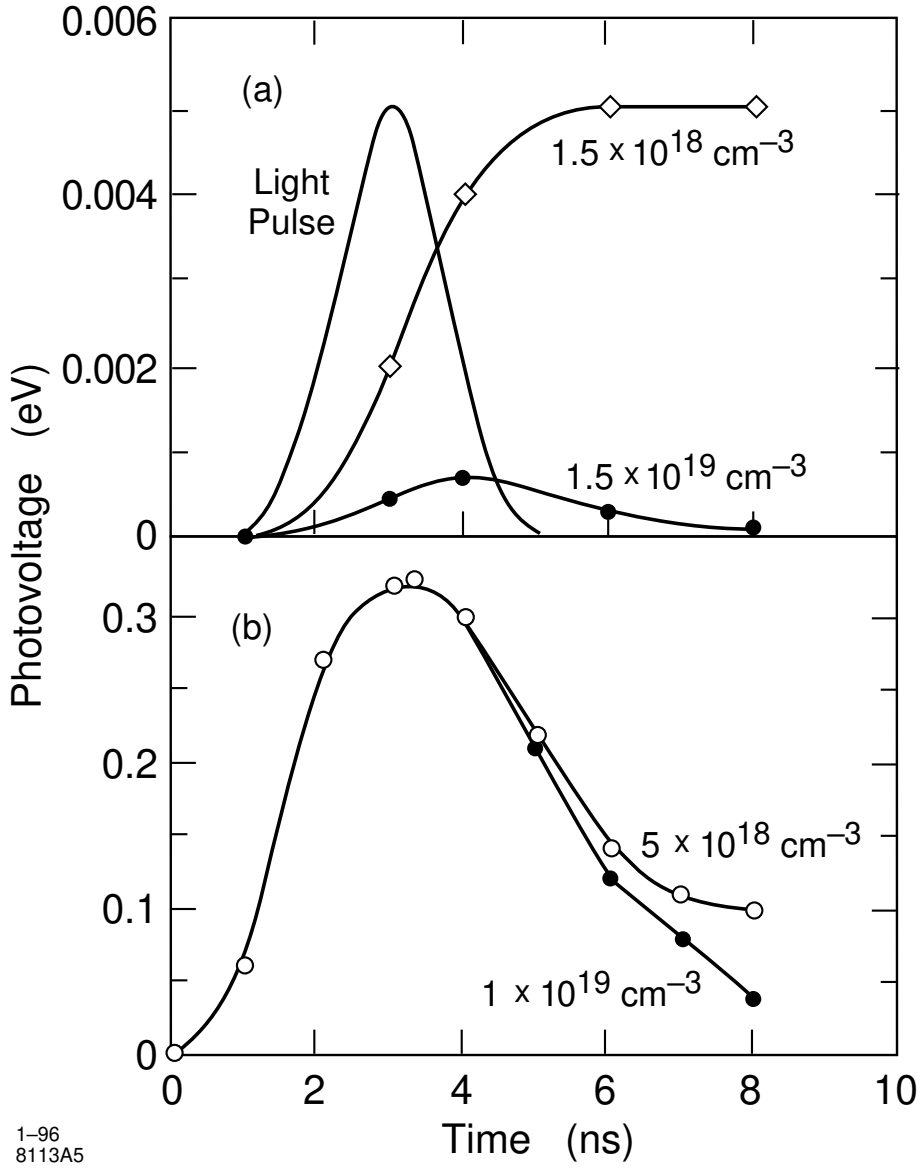

Figure 5. (A) Temporal photovoltage variation for two cathodes with different p-doping levels. The light is a 1-μJ Gaussian pulse (dotted line) and the cathode is not working at the saturation region. The differences in restoring time come mainly from the tunneling current. (B) The same as A, but the pulse is 90 μJ, the PV is more the 0.3 eV, and the cathode is working deeper at the saturation region. The amount of charge coming to the surface from the bulk is so large that the photovoltage almost neutralizes the band bending. When the band bending is *restored*, the tunneling current becomes more important, and the higher the p-doping level, the shorter the restoring time.

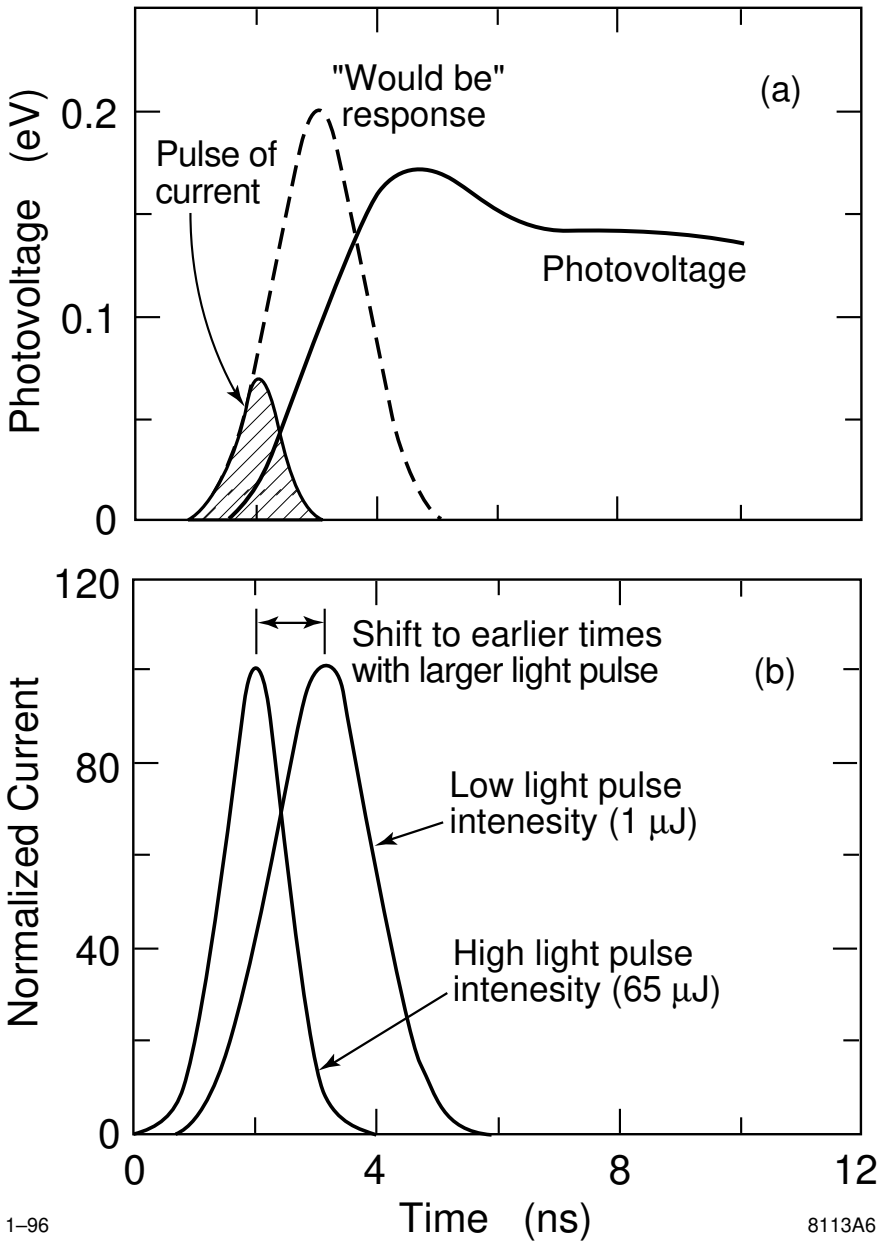

Figure 6. (A) The charge pulse peaks earlier than the light pulse—as PV increases, the yield decreases. The final result is that charge pulse becomes narrower and peaks at an earlier time. (B) This effect is more remarkable as the incident light intensity increases.

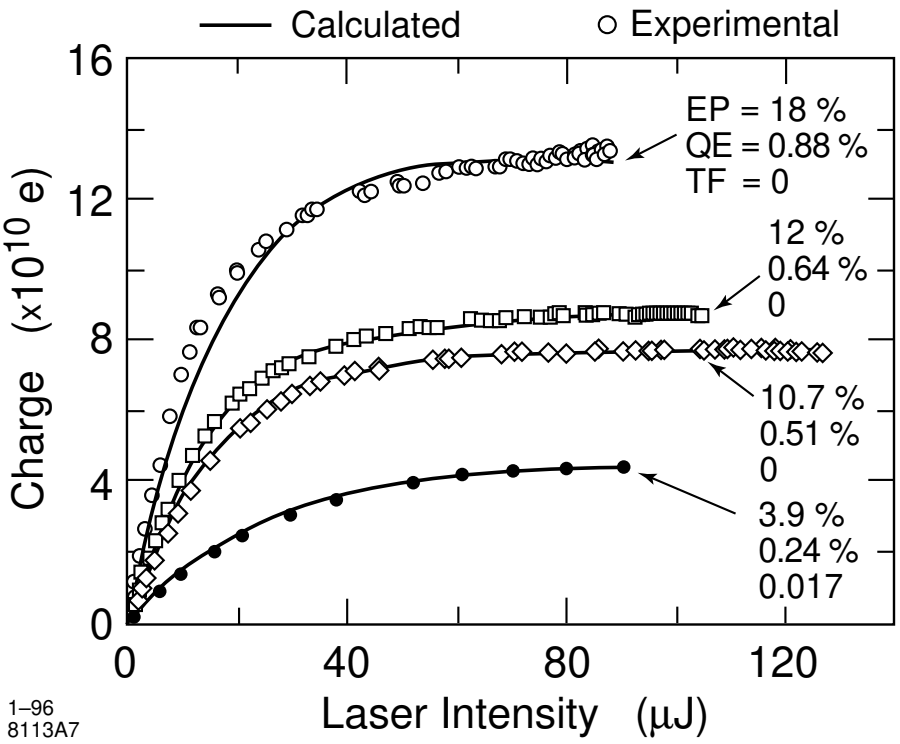

Figure 7. The light intensity is plotted against the charge. The points indicate experimental results, and the curve is plotted versus the calculated result. The most remarkable results are the TF values obtained. The lowest QE case (triangles) fit corresponds to a TF ≠ 0. This appears to be related to a *metal-like* density of occupied surface states, Case B(2) in Figure 3. For the case of higher QEs, the picture is similar to that described in Figure 3(B1).

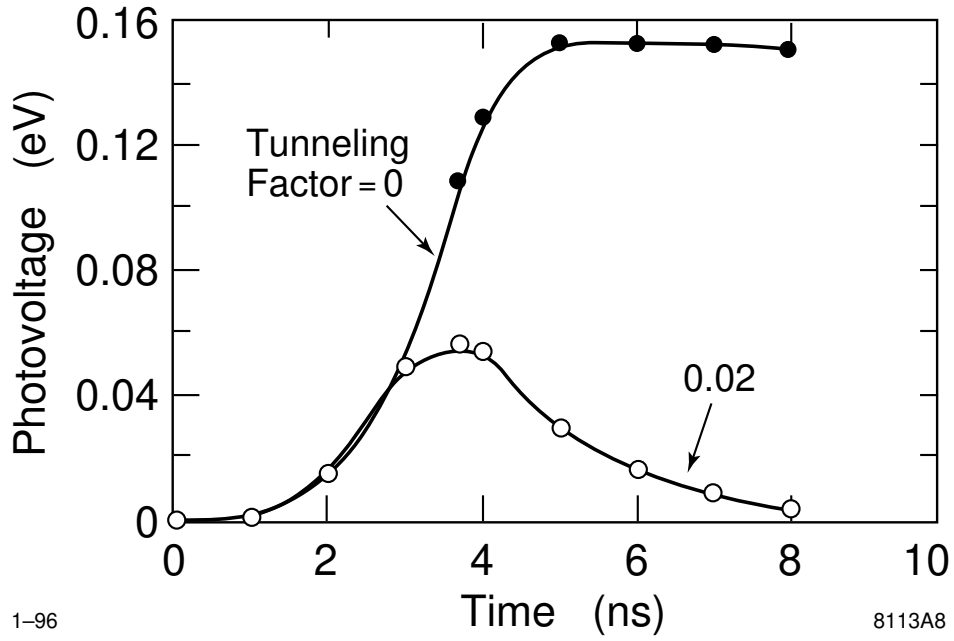

Figure 8. When present, the tunneling current is the most important restoring mechanism for high doping levels. We can see the calculated restoration time for the same cathode, using different TF values. When TF = 0, the thermionic current is the only restoring mechanism and the restoring time is long. If TF ≠ 0, the restoring time is much shorter. Thus, the presence of a metallic density of occupied states at the surface (TF ≠ 0) is important in order to avoid the CL effect.

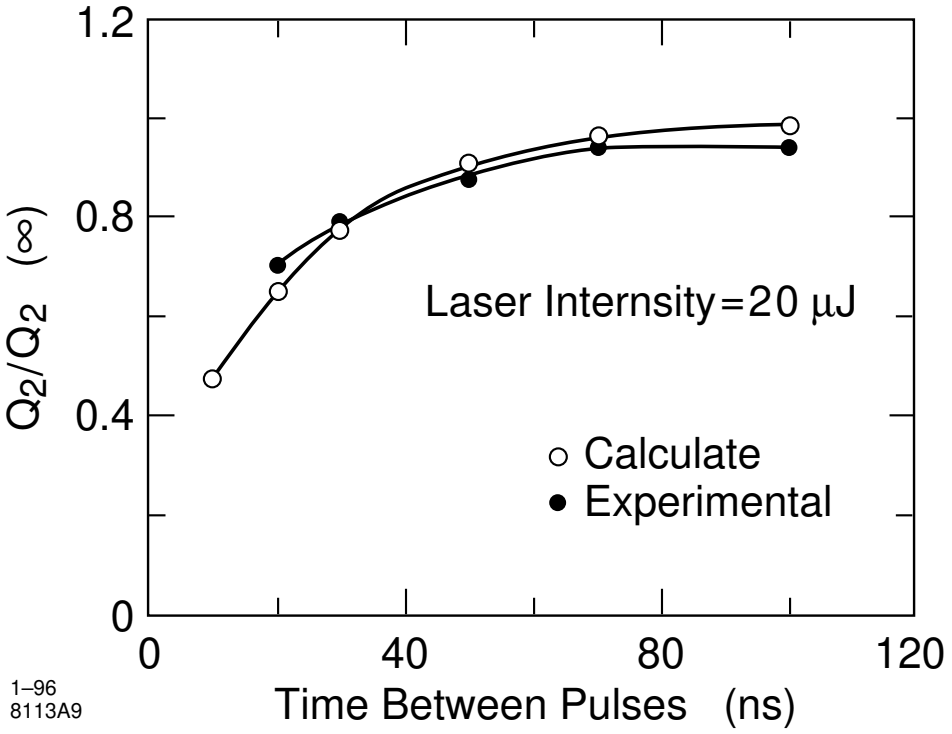

Figure 9. Due to the restoring time is not being zero, the first of two closely spaced bunches affects the second bunch. $Q_2(t)$ is the charge drawn to the cathode corresponding to a second pulse of light triggered in a time *t* from the first one. We see that the agreement between the simulation and the experiment is also good for a train of pulses.

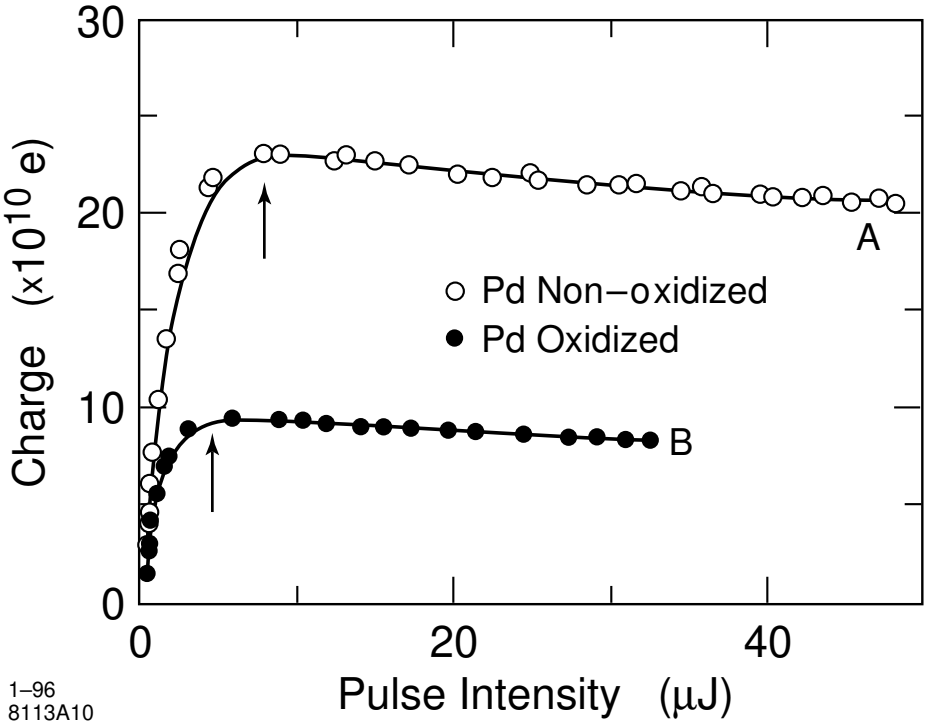

Figure 10. When a thin metal layer is deposited on the surface, the saturation point (arrows) and the total charge drawn from the cathode are modified. The yield for low light levels is higher in the case where Pd is oxidized, but for high light levels, the quicker restoring time for case where Pd is pure metal permits more charge to be drawn seems to be When the cathode is working at high light levels, the tunneling referred to in Figure 3(B2) occurs more readily.