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Increasing Photocathode Charge Output*

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Abstract

A fundamental concern in the operation of electron accelerators is the generation of intense beams with high polarization. The time structure of the electron beam determines whether the limiting factor in emission is laser power or surface charge buildup. The presence of excess surface charge comes about due to the photon absorption that excites electrons from the valence to the conduction band. Some fraction of the electrons can be trapped near the surface which induces a rise in the electron affinity through the increased electrostatic potential. The higher affinity causes a lower emission probability and thus less emitted charge at later times. The electron affinity can recover to the zero charge limit after electron-hole recombination. As an example, the Next Linear Collider requires 95 micropulses having 2×10^{10} electrons per pulse in 0.7 ns with an interpulse spacing of 2.8 ns. Experience at SLAC has shown it is possible to generate 16×10^{10} electrons in 2 ns pulses with the requisite polarization. However, subsequent pulses may experience strong intensity damping. Several parameters can be varied to enhance the net charge output of the later pulses. Among these are increasing either the electric field at the photocathode surface or the surface charge dissipation rate by raising the carrier concentration or shunting the trapped charge. We present a series of measurements and a phenomenological model to characterize the range of these influences.

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1 Introduction

A fundamental concern in the operation of electron accelerators is the generation of intense beams with high polarization. The time structure of the electron beam determines whether the limiting factor in emission is laser power or surface charge buildup. The presence of excess surface charge comes about due to the photon absorption that excites electrons from the valence to the conduction band. Some fraction of the electrons can be trapped near the surface which induces a rise in the electron affinity through the increased electrostatic potential. The higher affinity causes a lower emission probability and thus less emitted charge at later times. The electron affinity can recover to the zero charge limit after electron-hole recombination. As an example, the Next Linear Collider requires 95 micropulses having 2×10^{10} electrons per pulse in 0.7 ns with an interpulse spacing of 2.8 ns. Experience at SLAC has shown it is possible to generate 16×10^{10} electrons in 2 ns pulses with the requisite polarization. However, subsequent pulses may experience strong intensity damping. Several parameters can be varied to enhance the net charge output of the later pulses. Among these are increasing either the electric field at the photocathode surface or the surface charge dissipation rate by raising the carrier concentration or shunting the trapped charge. We present a series of measurements and a phenomenological model to characterize the range of these influences.

2 Charge Limit Parameterization

The surface charge buildup's effects on charge output may be studied by using the pump-probe technique in which one laser is used to emit a pulse (the pump) and a second laser is used to excite a subsequent pulse (the probe) which quantifies the attenuation. The charge in the probe beam can be expressed as

$$\frac{Q}{Q^{\infty}} = 1 - AQ_0 e^{-\frac{\Delta t}{\tau}},$$

where Q^{∞} is the charge emitted in the absence of the pump beam and Δt is the delay between the pump and probe. The decay of the surface photovoltage is characterized by τ. The parameter A encapsulates many of the material properties such as sensitivity to extracted charge and is a strong function of the doping concentration.

A series of closely spaced pulses, the limiting case of which is a continuous pulse, can be modeled by considering the contribution of the earlier pulses individually so that a pulse n emits a charge Q_n which depends on the charge and time interval of bunches $i = 0 \dots n-1$ as well as on the laser excitation energy for the nth bunch. The interval $\Delta t_{i,i'}$, is defined to be $t_i - t_{i'}$. The charge in the nth bunch is expected to be

$$\frac{Q_n}{Q_n^{\infty}} = 1 - A \sum_{i=1}^{n} Q_{i-1} e^{-\frac{\Delta t_{n,i-1}}{\tau}}.$$

Applying this system of equations to pump-probe data acquired from strained GaAs allows us to extract A and τ by performing an exponential fit to the data. There is a clear decrease in A and τ going from $5 \times 10^{18}/\mathrm{cm}^3$ to $2 \times 10^{19}/\mathrm{cm}^3$ doping. As a check, we applied these parameters to data measured using a 200 ns long laser pulse which is the length of an NLC pulse, but without the interpulse gaps. The agreement between the experimental data and the predicted response from the phenomenological parameters is good. This lends confidence to modeling the high charge (but lower than the pump-probe values) NLC type beam. The $5 \times 10^{18}/\mathrm{cm}^3$ doped material cannot produce the NLC pulse train, but the $2 \times 10^{19}/\mathrm{cm}^3$ material can. These results led us to determine doping dependencies in the absence of complicating factors.

3 Dopant Concentration Dependencies

A series of measurements were performed using unstrained 100 nm thick GaAs to ascertain the doping dependence on surface photovoltage recovery time independent of complicating factors such as strain and heterostructure. The data were acquired using the 121 kV diode gun in the SLAC Gun Test Laboratory with the photocathode temperature held at 0°C. Both the pump and probe beams were set to 850 nm, so that with the cathode cooled, this corresponds to an offset of 15 nm from the band gap energy. Yield and polarization data were also acquired in the Cathode Test Lab over a range of 650 to 900 nm. The variation of the polarization with doping concentration was minimal with a greater variation seen in the near gap yield corresponding to the change in the absorption edge state density. The pump-probe data show a clear trend in the parameters A and τ with both decreasing over the $5 \times 10^{18}/\mathrm{cm}^3$ to $5 \times 10^{19}/\mathrm{cm}^3$ range measured. At the highest doping concentration there is very little attenuation apparent. This suggests that high doping, particularly at the surface, should be sufficient to enable a cathode to generate NLC type charge. However, there are conditions under which such a treatment may not be desirable.

4 Charge Bleedoff Grid

An alternate to the increased doping level is the addition of a direct, lateral surface charge sink in the form of a metallic grid overlaid on the surface. The creation of such a grid presents several challenges. First, the grid must be small enough that the spacing between the lines allows charge diffusion during the time of interest, a few nanoseconds. This requirement may be accomplished by using standard lithographic methods. The second requirement is that the grid material make good electrical contact, yet not mix with the GaAs at the heat cleaning temperature, 600°C, lest the exposed GaAs surface become coated with the grid material. Lastly, the material must be robust enough to withstand the heat cleaning process by having a very low vapor pressure at 600°C. The material that met all these requirements is tungsten. The grids were prepared on 100 unstrained GaAs with a doping level of $1 \times 10^{18}/\mathrm{cm}^3$ to deliberately exacerbate the surface charge buildup. The line width was 10 μm with a 23 μm spacing which left 38% of the GaAs exposed. The lines were 30 nm high. Initial testing consisted of stability of the structure after heat cleaning for one hour and the ohmic quality of the contact. Measurement of the charge output as a function of the laser intensity showed appreciable gain over a sample prepared under the same conditions as the grid covered material. The peak charge measured at 862 nm was enhanced by around 30%, while at 790 nm a factor of two increase was achieved. Further improvements will include smaller line widths and closer spacing.

More Charge, Who Cares?

What is 'More Charge'?

I. High current density
- A. Prevalent effect in nanosecond scale systems
- B. Can be a problem in microsecond & cw systems

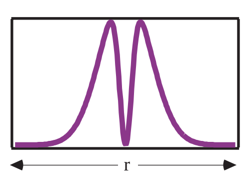
II. Cumulative charge emission
- A. No apparent memory effect
- B. Damage from non-ideal vacuum environment

Who needs 'More Charge'?

I. cw accelerators benefit from higher QE
- A. Large band gap
- B. Bragg reflector

II. Next generation linear colliders
- Injector requirements not yet achieved (JLC/NLC)

III. Integrated circuit fabrication
- Cold source electron beams need high current density



NLC Injector Systems

Next Linear Collider

Polarized Electron Injector Parameters

Energy	E	120	keV
Energy Spread	$\Delta E/E$	< 1	%
Single Bunch Spread	$\sigma E/E$	< 1	%
Emittance (edge)		5	10^{-6} m-rad
Bunch Length	Δt	700	ps (fwhm)
Particles/Bunch	nb	2.0	10^{10}
Pop. Uniformity	$\Delta nb/nb$	< 0.5	%
Number of Bunches	Nb	95	
Bunch Spacing		2.8	ns
Repetition Rate		120	Hz
Polarization		80	%

Present Understanding

Closest charge density match to NLC

SLC: 1.6x10^{11} e^-/bunch in 2 ns

Adjustable parameters that effect charge

I. QE through electric field

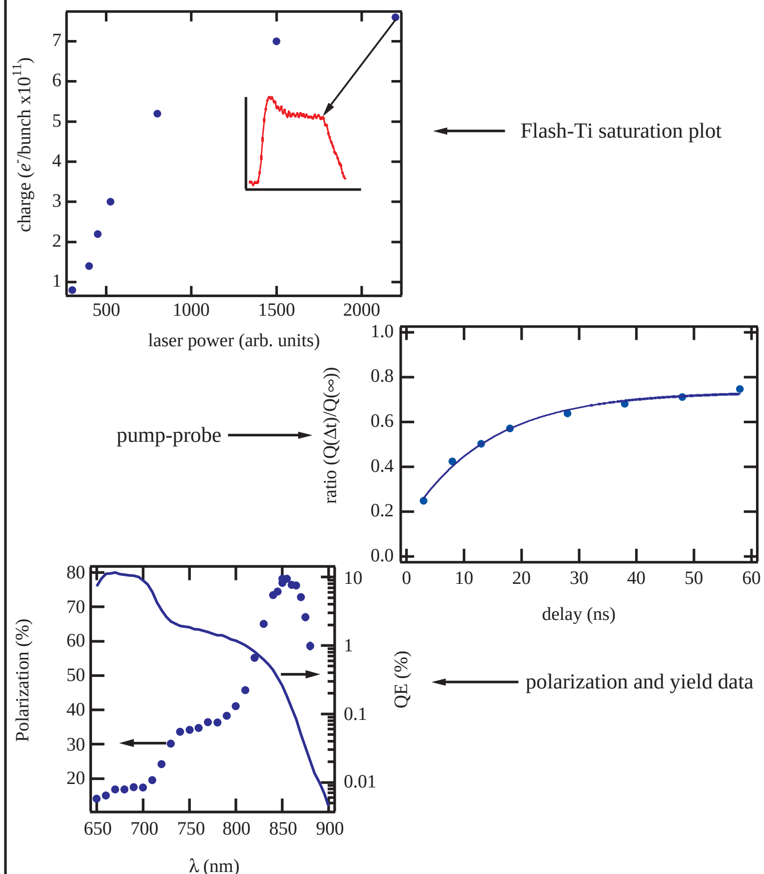
II. QE through Bragg reflector (‘used’ photons)

III. Charge through doping concentration

IV. Charge through large band gap

V. Charge through electric field

Spire M05-3151 strained GaAs
QE at 833 nm = 0.6% with cathode at 121 kV
Measured in GTL with a laser pulse width = 200 ns



Phenomenological description

- All preceding charge influences subsequent pulses
- Characterize recovery as exponential with constant τ
- Constant τ extracted from pump-probe data
- Region of validity is for emission (no extremes)
- Governing equation

$$\frac{Q_n}{Q_n^{\infty}} = 1 - A\sum_{i=1}^{n} Q_{i-1} e^{-\frac{\Delta t_{n,i-1}}{\tau}},$$

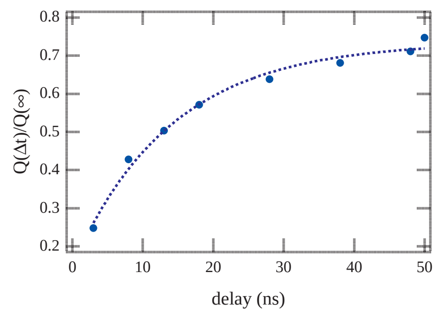
where Q_n^{∞} is the charge that would be emitted with no preceding pulses and A encompasses material parameters

- Reduction to pump-probe case

$$\frac{Q}{Q^{\infty}} = 1 - AQ_0 e^{-\frac{\Delta t}{\tau}}$$

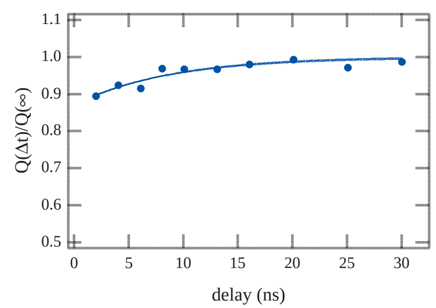
Simulations

- Extraction of parameters τ and A



Strained layer GaAs with 5×10^{18}/cm^3 doping. P_{e^-} = 78 %

τ = 14.1 ns; $A = 2.6\times10^{-2}$ nC^{-1}

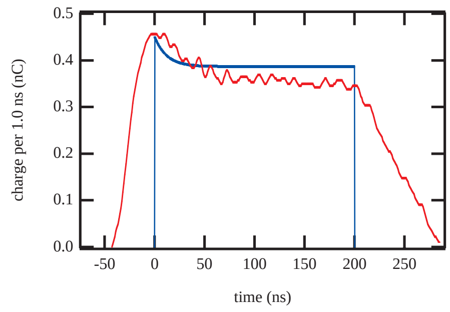


Strained layer GaAs with 2×10^{19}/cm^3 doping. P_{e^-} = 64 %

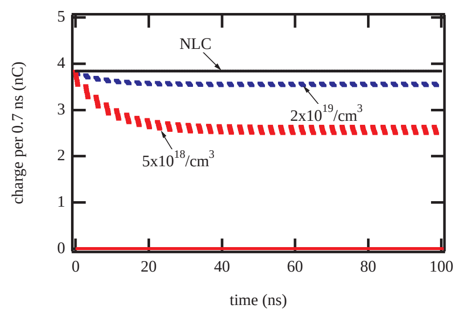
τ = 8.7 ns; $A = 6.9\times10^{-3}$ nC^{-1}

Simulations

• Long pulse charge output comparison



• NLC charge output trials



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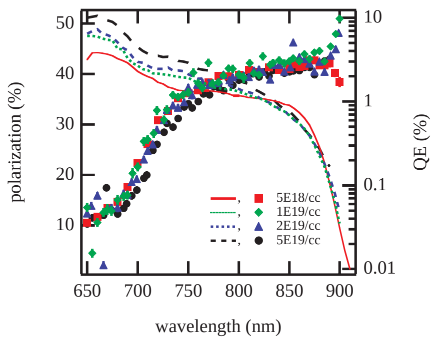
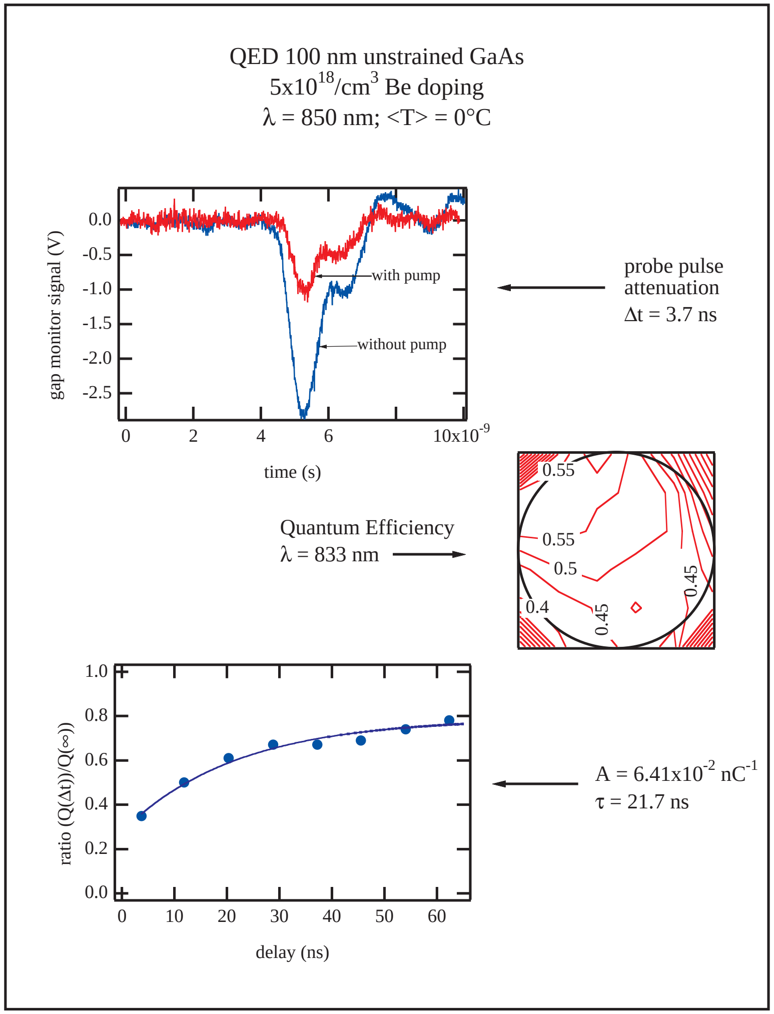
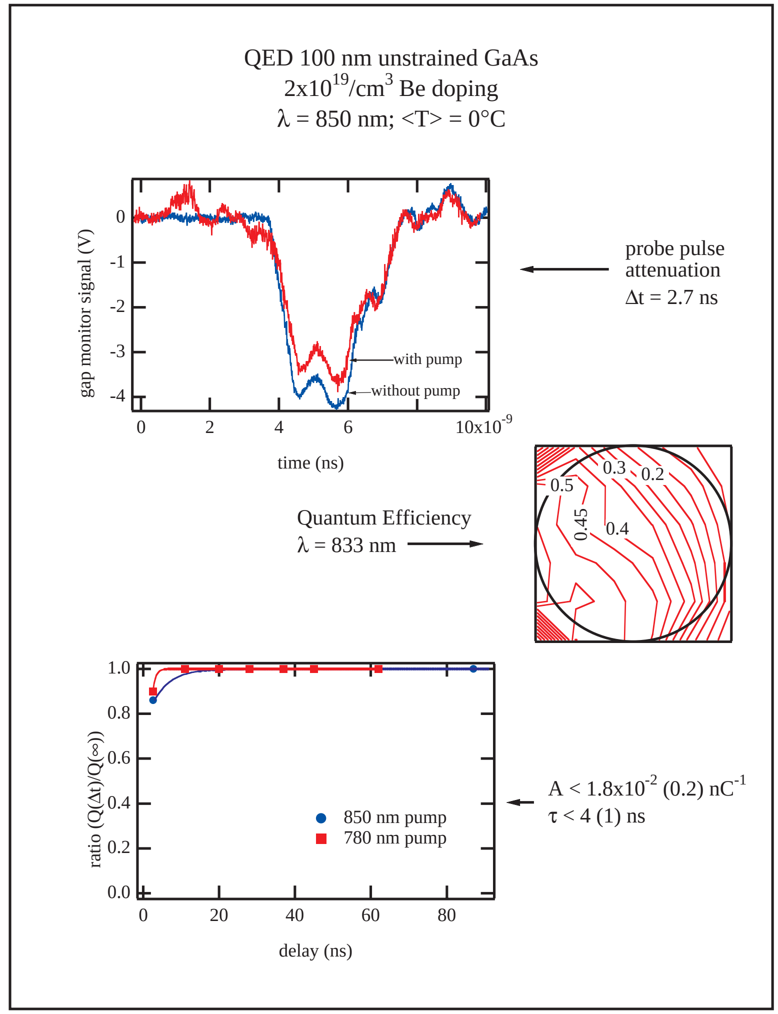
Comparison of doping level effects
on QE and polarization
QED 100 nm unstrained GaAs



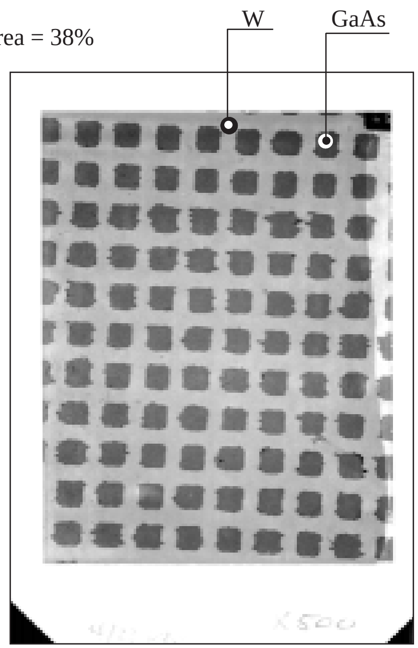

QED 100 nm unstrained GaAs
5x10^18/cm^3 Be doping
λ = 850 nm; <T> = 0°C
gap monitor signal (V)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
2
4
6
10x10^-9
time (s)
with pump
without pump
probe pulse attenuation
Δt = 3.7 ns
Quantum Efficiency
λ = 833 nm
0.55
0.55
0.5
0.4
0.45
0.45
ratio (Q(Δt)/Q(∞))
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
delay (ns)
A = 6.41x10^-2 nC^-1
τ = 21.7 ns


QED 100 nm unstrained GaAs
2x10^19/cm^3 Be doping
λ = 850 nm; <T> = 0°C
gap monitor signal (V)
0
-1
-2
-3
-4
0
2
4
6
10x10^-9
time (ns)
with pump
without pump
probe pulse attenuation
Δt = 2.7 ns
Quantum Efficiency
λ = 833 nm
0.5
0.3
0.2
0.45
0.4
ratio (Q(Δt)/Q(∞))
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
delay (ns)
850 nm pump
780 nm pump
A < 1.8x10^-2 (0.2) nC^-1
τ < 4 (1) ns

Charge Bleedoff Grid

aka Microscopic Current Shunts

- Tungsten choosen for robustness and for low reactivity
- Lithographic techniques used for deposition
- Line width = 10 µm with 23 µm spacing
- Line height = 30 nm
- Clear area = 38%



Current density enhancement using W grid
QED 100 nm unstrained GaAs
$1x10^{18}/cm^3$ Be doping