

A diffusion model for picosecond electron bunches from negative electron affinity GaAs photo cathodes

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Abstract

Even though theoretical estimates predict response times for the photo emission process of electrons from a negative electron affinity GaAs photo emitter in excess of hundreds of picoseconds, recent measurements found electron bunch durations of 40 ps or less.

This work presents precise measurements of picosecond electron bunches from a negative affinity bulk GaAs photo cathode and develops a model which explains the measured bunch durations as well as the observed bunch shapes. The bunch shape turns out to be independent from the quantum efficiency of the photo emitter.

1 Introduction

Photo emission of electrons from solids has found wide application in Physics. Besides practical application, as in photomultiplier tubes or night vision devices, photo emission is used to study the properties of the photo emitter itself.

Even though the quantum theory of the photo effect was published in 1905 [1], it was regarded up to the fifties as a pure surface effect.

W. E. Spicer first understood photo emission as a bulk effect and developed his Three-Step-Model [2] of photo emission (see fig. 1a). Virtually any attempt to apply this diffusion model to negative electron affinity photoemitters [3, 4] failed in describing the photoresponse to a light pulse of sub-picosecond duration. The predicted response times ranged from several hundred picoseconds up to tens of nanoseconds, and were sometimes even dependent on the quantum efficiency of the photo cathode (see figure 1b).

On the other hand, recent measurements [5, 6, 7, 8] have found bunch durations less than 40 ps from negative affinity photo emitters.

Although the Three-Step-Model describes photo emission from solids in general correctly, it may not be applied to negative affinity semiconductors without additional assumptions.

This work presents precise measurements of picosecond electron bunches from a negative affinity GaAs photo cathode and develops a model which explains the measured bunch durations as well as the observed bunch shapes.

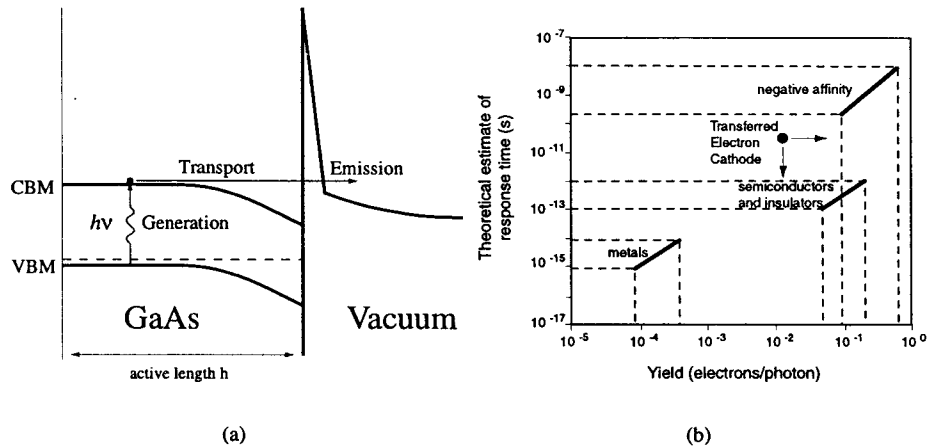


Figure 1: (a) The Three-Step-Model regards photo emission as made up of photogeneration, electron transport and electron emission (b) Prediction of the response time of several photoemitters (from ref.[4]).

2 Experimental setup and results

The measurements were performed at the pulsed electron gun test facility at MAMI [8, 9]. Its principle of operation is sketched in figure 2. It allows the analysis of short polarized electron bunches generated by illumination of a photo cathode with short laser pulses. The generated electron beam is wobbled with help of a TM_{110} radio frequency resonator over the narrow entrance slit of an electron spectrometer. Since the laser pulse repetition rate is synchronized to the wobble radio frequency, a stable spatial image of the bunch is generated. This spatial pulse image can be shifted over the slit by varying the phase of the laser pulses relative to the radio frequency. By measuring the dependence of the current, transmitted through the slit, on the phase shift, the bunch profile is sampled. A detailed description of the setup may be found in reference [9]. For these measurements the laser spot on the cathode was Gaussian shaped and had a diameter of $100 \mu\text{m}$ FWHM. The laser pulse duration was measured with an autocorrelator to be 5 ps FWHM assuming a Gaussian pulse shape.

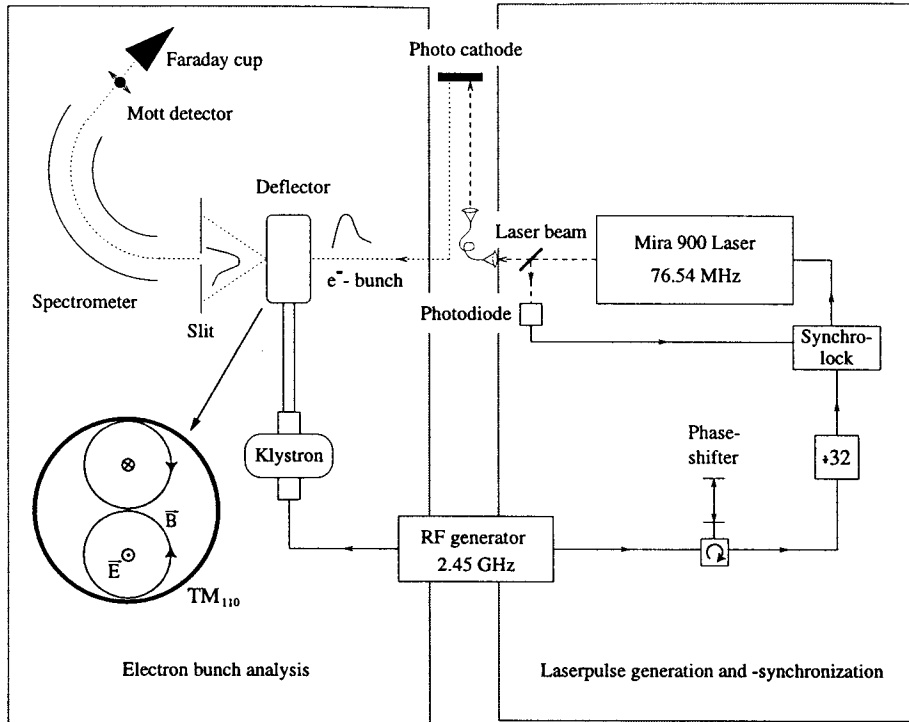


Figure 2: Sketch of the experimental setup

In order to ensure the absence of bunch deformation by space charge effects, all measurements were made at bunch charges of several femto coulombs. In this regime, a dependence of the bunch shape on the bunch charge was not observed. Figure 3 shows a typical bunch profile obtained from a bulk GaAs photo cathode. It has a steep leading edge and a slowly decreasing trailing edge. The line shows a fit of the diffusion model described below to the data.

In order to obtain the data shown in Fig. 4 the wafer was activated in a separate preparation chamber of a load lock system attached to the electron gun [9]. A Yo-Yo preparation with Cesium and Oxygen gave a quantum efficiency of 15 % at 633 nm. After the activation the wafer was moved to the gun chamber. The data were taken at two different laser wavelengths, 800 nm and 840 nm respectively. After each measurement the photo cathode was aged by running 50 μ A beam from the gun which resulted in a decrease of the quantum efficiency of the photocathode. In figure 4, bunch shapes obtained at four different quantum efficiencies for each wavelength are presented.

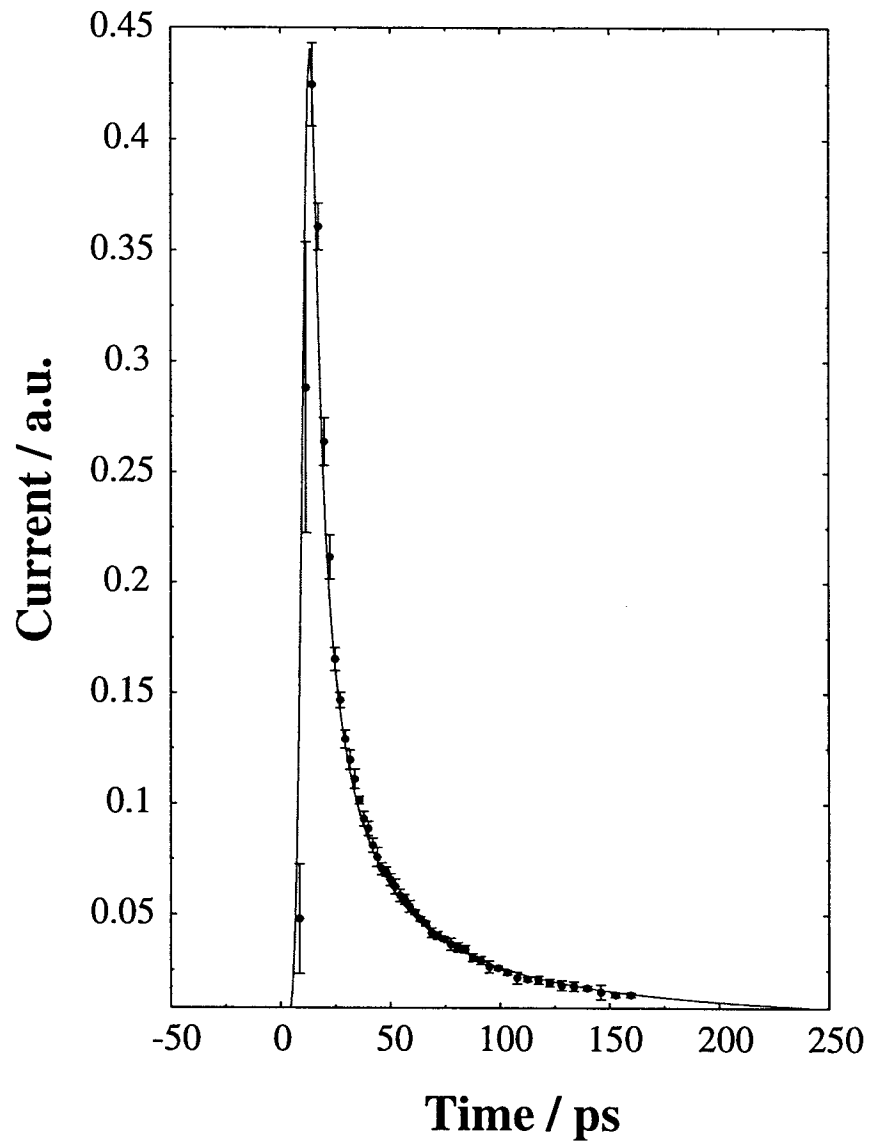


Figure 3: A typical bunch shape obtained from a negative affinity bulk-Galliumarsenide photo cathode. The line marks a fit to the data obtained by the model for $D = 200 \text{ cm}^2/\text{s}$.

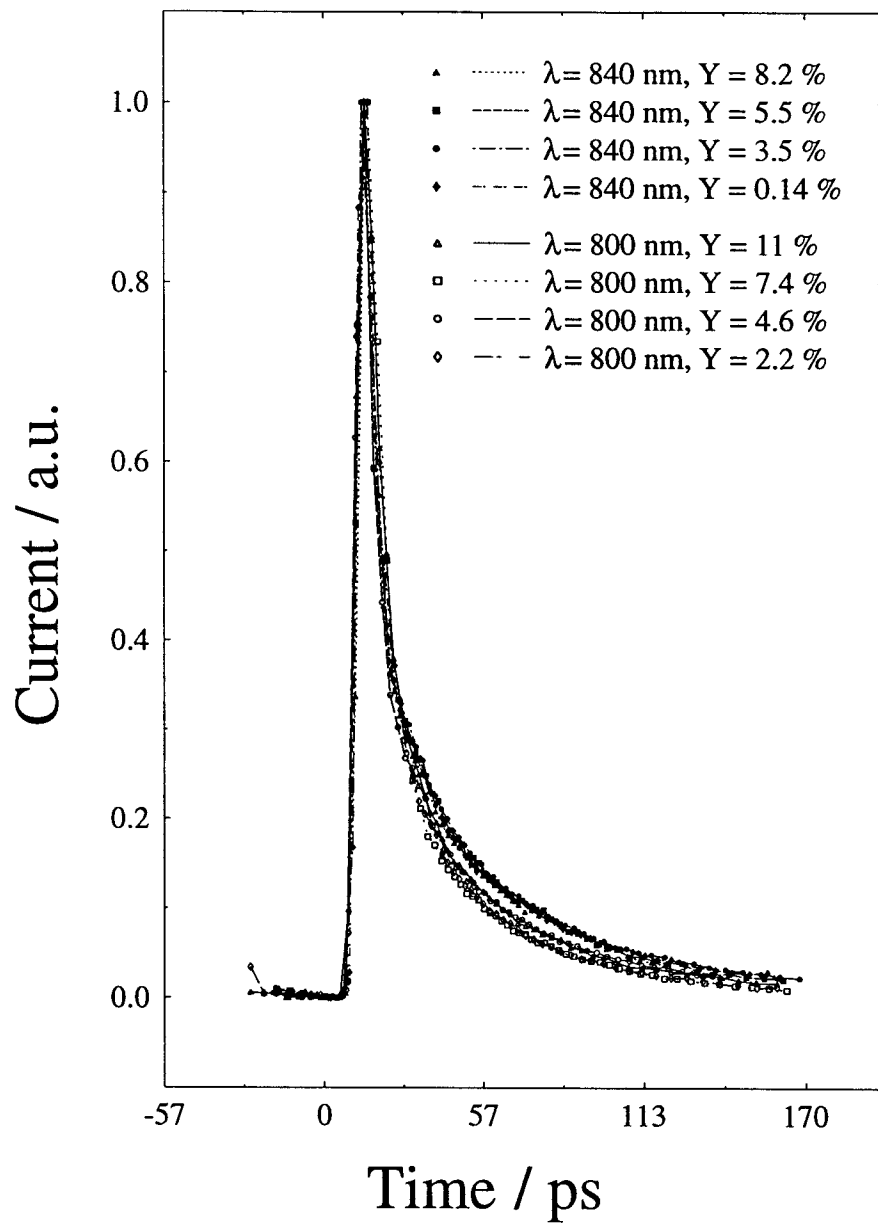


Figure 4: Electron bunches measured at four different quantum efficiencies and at two different laser wavelengths.

3 Model calculation

Within the Three-Step-Model the photo generation and diffusion of electrons in a semiconductor may be well described by the general equation [4]

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

The electron concentration $c(r,t)$ as a function of space and time consists of three terms. The first term

$$g(r,t) = \alpha I_0 e^{-\left(\frac{t-t_0}{\tau_0}\right)^2} e^{-\alpha z} \quad (2)$$

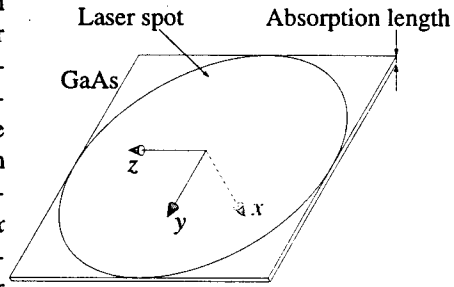
is a generation term. An incident Gaussian shaped laser pulse of intensity I_0 and duration τ_0 is absorbed in the semiconductor. It generates an exponentially decreasing number of electrons as it penetrates into the photo cathode. The absorption constant α determines the strength of the light absorption in the wafer.

The second term $\frac{c(r,t)}{\tau}$ stands for the electron annihilation, where τ is the electron lifetime.

The third term $D\nabla^2 c(r,t)$ describes the electron displacement by diffusion. D stands for the electron diffusion constant. Both, the light absorption constant α and the electron diffusion constant D depend upon the temperature and the doping concentration of the wafer.

In the case of pulse generation from a negative affinity GaAs photo cathode in a real electron gun, some simplifications and assumptions can be made to get towards an equation for the pulse profile:

1. Electrons are usually generated by illuminating the photo cathode with a laser beam. Since the laser spot diameter at the cathode usually is large compared to the absorption length of the light in the wafer ($\alpha^{-1} \approx 1\mu\text{m}$), the diffusion process may be described by a one-dimensional model. The variable x therefore is taken as the spatial coordinate, perpendicular to the wafer surface.



2. Since the electron recombination lifetime is some orders of magnitude larger than the observed bunch durations [5, 6, 7, 8], the electron recombination term $\frac{c(r,t)}{\tau}$ is neglected.
3. The photo generation term can be split into two parts. The exponential absorption is regarded by generating an exponentially decreasing concentration distribution as the initial condition.

$$c(x, t = 0) = \phi(x) = c_0 e^{-\alpha x} \quad \text{for } x \in [0, h] \quad (3)$$

The laser pulse profile is in a later step convoluted with the electron current obtained from the diffusion equation.

4. Most important for the model of a negative affinity photo emitter is to take the formation of a band bending region at the activated surface of the semiconductor into account. Due to this surface effect most electrons, once they reach the semiconductor surface, either lose energy in the band bending region [10, 11] and are trapped at the surface, or are emitted from the cathode. However, they are not able to diffuse back into the bulk.

This fact can be taken into account by solving equation 5 in a layer of limited thickness h with $c(x, t) \equiv 0$ on both layer surfaces.

$$c = 0 \quad \text{for } t > 0 \text{ and } x = 0 \text{ or } x = h. \quad (4)$$

To simulate a thick GaAs wafer the layer thickness h is made large compared to the light absorption length α^{-1} .

According to conditions 1-3 equation 1 can be reduced to

$$\frac{\partial c(x, t)}{\partial t} = D \frac{\partial^2 c(x, t)}{\partial x^2}. \quad (5)$$

It is solved with a separation ansatz which leads to the solution

$$c(x, t) = [A \sin(\lambda x) + B \cos(\lambda x)] \cdot e^{-\lambda^2 D t}. \quad (6)$$

B and λ are determined by conditions 3 and 4, leading to

$$B = 0 \quad \text{und} \quad \lambda = \frac{n\pi}{h}. \quad (7)$$

The general solution is then given by

$$c(x, t) = \sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi}{h} x\right) e^{-\left(\frac{n\pi}{h}\right)^2 D t}. \quad (8)$$

According to condition 3

$$\phi(x) = c_0 e^{-\alpha x} = \sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi}{h} x\right) \quad \text{for } 0 < x < h. \quad (9)$$

This leads to an expression for the constants A_n :

$$A_n = \frac{2}{h} \int_0^h \phi(x) \sin\left(\frac{n\pi}{h} x\right) dx \quad (10)$$

$$= 2 c_0 \underbrace{\frac{n\pi e^{\alpha h} - n\pi \cos(n\pi) - \alpha h \sin(n\pi)}{\alpha^2 h^2 + n^2 \pi^2}}_{C(\alpha, h, n)} e^{-\alpha h}. \quad (11)$$

Inserted in equation 8 we find

$$c(x,t) = 2c_0 \sum_{n=1}^{\infty} C(\alpha, h, n) \sin\left(\frac{n\pi}{h}x\right) e^{-\left(\frac{n\pi}{h}\right)^2 Dt}. \quad (12)$$

In figure 5, the electron concentration in the wafer is plotted versus x for four different times and randomly chosen parameters α, D and h . The boundary condition $c(x,t) = 0$ at the surface of the wafer leads to a steep concentration gradient pointing towards the wafer surface. This gradient is finally responsible for the generation of a short intense

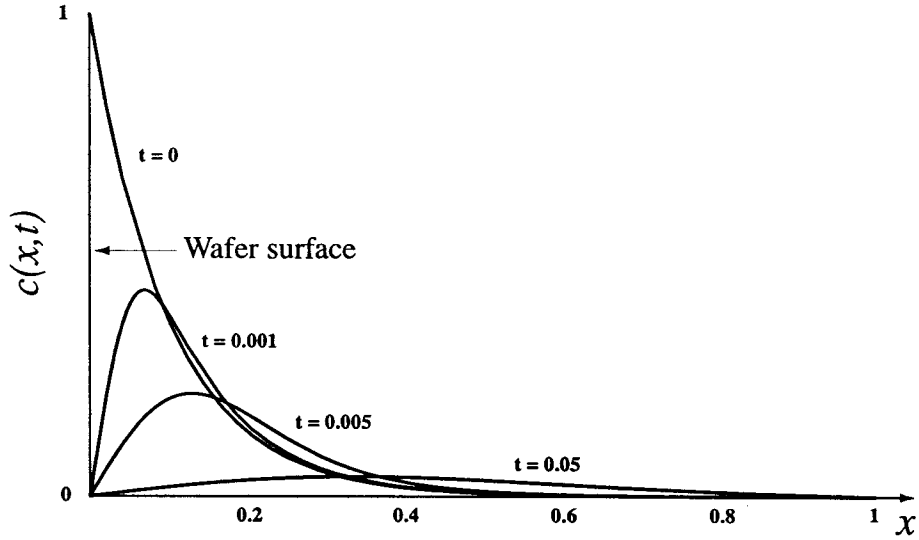


Figure 5: Electron concentration for randomly chosen parameters α, D and h at four different times t .

electron bunch emitted from the wafer.

The total number of particles in the layer is given by

$$N(t) = \int_0^h c(x,t) dx \quad (13)$$

$$= -2c_0 \sum_{n=1}^{\infty} C(\alpha, h, n) \frac{h}{n\pi} \cos\left(\frac{n\pi}{h}x\right) e^{-\left(\frac{n\pi}{h}\right)^2 Dt} \quad (14)$$

Since this model neglects any electron sinks in the wafer except electron emission from the surface, the emitted photo current may be obtained by differentiation of $N(t)$ with respect to t .

$$I(t) \propto \frac{\partial}{\partial t} N(t) = \frac{\partial}{\partial t} \int_0^h c(x,t) dx \quad (15)$$

$$= 2c_0 \sum_{n=1}^{\infty} C(\alpha, h, n) \frac{n\pi}{h} D \cos\left(\frac{n\pi}{h} x\right) e^{-\left(\frac{n\pi}{h}\right)^2 D t} \quad (16)$$

Figure 6 shows the emitted photocurrent as a response to a delta light pulse. As the last

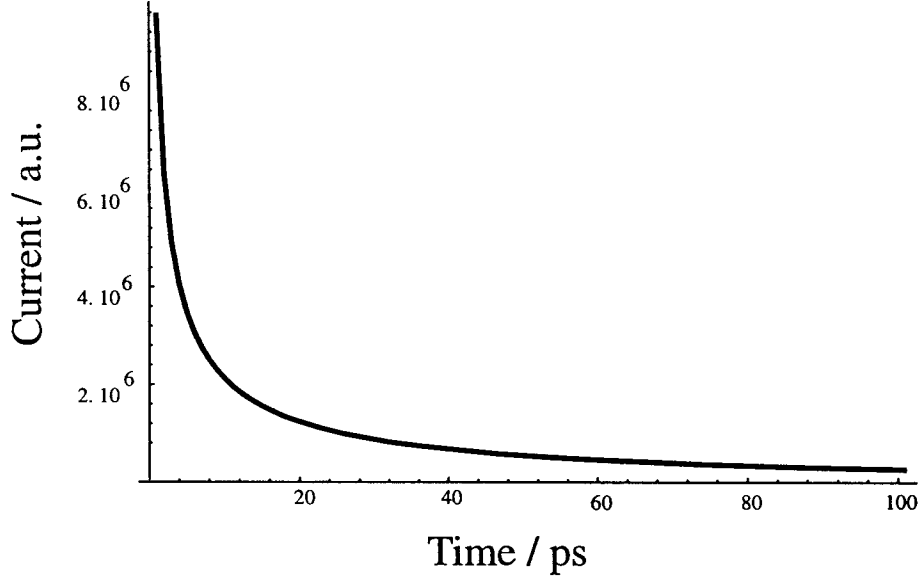


Figure 6: Bunch profile obtained from the model for an infinitely short laser pulse ($D = 200 \text{ cm}^2/\text{s}$).

step the obtained shape is convoluted with the Gaussian laser pulse shape as mentioned in condition 3, and with the phase resolution of the measurement setup. Truncating the series in eqn. 16 changes the slope of the leading edge of the calculated electron bunch from infinite to some finite value. Since this edge is in reality determined by the shape of the laser pulse, the series may be truncated, if the calculated leading edge stays short compared to the edge of the laser pulse. For this calculation the series was evaluated up to $n = 10000$, which ensured a leading edge of less than 1 ps. The fit of the model to the data was obtained by varying D for a given value of α , using a χ^2 -method.

4 Discussion

The eight bunches displayed in figure 4 split into two groups which are related to the two different wavelengths, 800nm and 840 nm, of the irradiating laser light. The 800 nm curves seem to split again into two subtraces. This splitting is not due to a change in quantum efficiency, but to small phase drifts during the bunch measurement.

We conclude from figure 4 that the bunch shape and hence the cathode response time does not depend on the quantum efficiency.

The different shape of the two groups may be explained by the larger light absorption

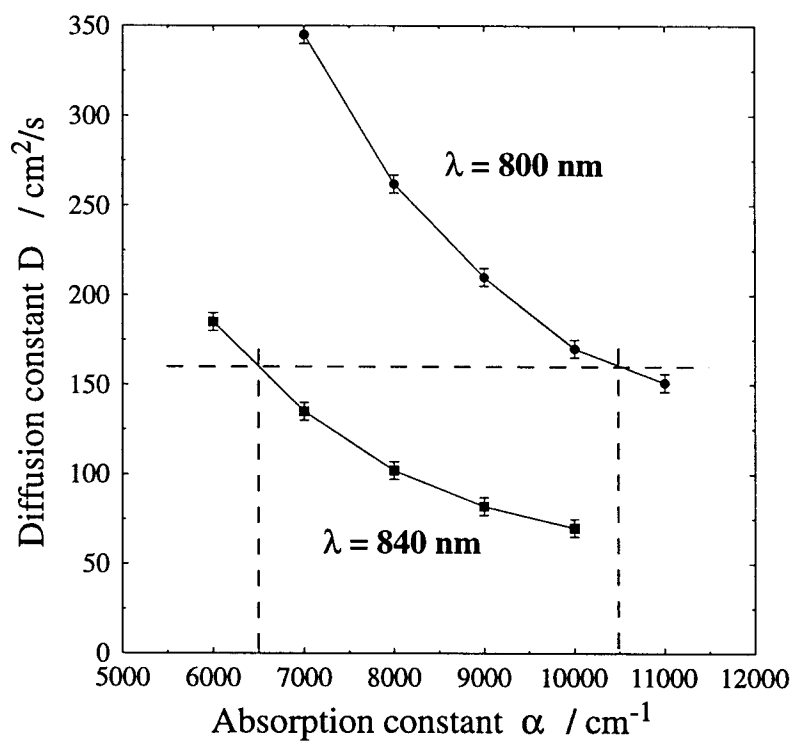


Figure 7: Fits with minimal χ^2 for different combinations of D and α to bunches generated at 800 nm and 840 nm. For $D = 155 \text{ cm}^2/\text{s}$ the absorption lengths agree well with data from literature.

length in the wafer at 840 nm. Fitting the above presented model to the data of figure 4 results in different sets of D and α at the same value of χ^2 (see figure 7). For $D = 155 \text{ cm}^2/\text{s}$ we find absorption constants $\alpha = 6500 \text{ cm}^{-1}$ for 840 nm and $\alpha = 10500 \text{ cm}^{-1}$ for 800 nm. These values are in good agreement with published values for the light absorption constant α at a p-doping level of $1.6 \times 10^{19} \text{ cm}^{-3}$ [12]. The value of $D = 155 \text{ cm}^2/\text{s}$ is close to the value for undoped GaAs of $200 \text{ cm}^2/\text{s}$, but electron mobility measurements give $D = 27 \text{ cm}^2/\text{s}$ for p-doped GaAs [13]. This discrepancy is not understood, yet.

The above model gives a good description of the bunch shape and hence of the response time of electron bunches generated with picosecond laser pulses from a negative electron affinity GaAs photocathode. The introduction of an electron sink at the wafer surface turned out to be a successful concept to model the photoemission process in a bulk photoemitter.

Its application to photocathodes with an active layer thickness of far less than the typical light absorption length, which are for example used to generate highly polarized electron beams for accelerator application, is not as simple, as to reduce the layer thickness h , though. The band bending region at the wafer surface, which extends several tens of nanometers into the material, becomes more and more dominant and cannot be described as a plane with zero thickness any more.

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