Minority Carrier Dynamics in Semiconductors
Shockley - Haynes Experiment

Pre - Lab

1. Aims

In this experiment, you will develop an understanding of the physics of minority carriers and their dynamics in semiconductors by carrying out the Shockley-Haynes experiment. You will use this your understanding to quantitatively measure the carrier mobility μ, diffusion constant D and lifetime τ of the minority carriers in a semiconductor.

2. Objectives

D μ

1. To use the equipment for the experimental investigation of the diffusion and drift of minority carriers in p and n-type germanium using a modified Shockley-Haynes technique.
2. To measure μ, D and τ of the minority carriers in a sample of Ge at room temperature.

3. Introduction

Important research in the 1950s

⇒ doping Ge material with impurities

Group III : boron group , moden day group 13

Group IV : carbon group , moden day group 14

Group V : nitrogen group , moden day group 15 groups III IV V

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	* 71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	** 103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			* 57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			** 89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Germanium : group IV

Acceptor , p-type (holes) , e.g. boron B : group V

Donor , n-type (electrons) , e.g phosphorus P : group III

Electronic device (light emitting diode - LED)

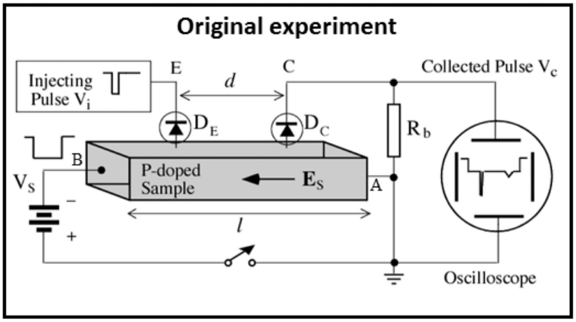
Minority carrier injection : injection of electrons/holes into regions of the semiconductor where holes/electrons are in majority

⇒ Understand how and how far the minorities move

1949 : Shockley and Haynes measured some dynamical properties of injected minority carriers

4. Experimental Details

Original set-up



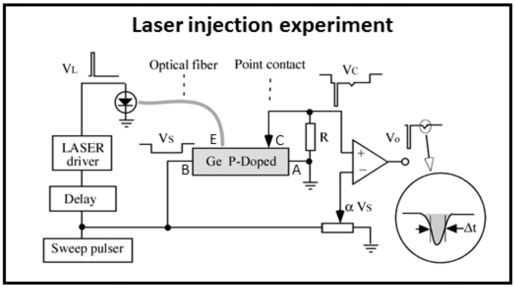
- Electric field $E_s = \frac{V_s}{\ell}$ created along bar of semiconductor by applying external voltage $V_s = V_{BA}$ between A and B separated by distance $\ell = |BA|$

- Excess injected at point E, carriers swept along bar by E-field
- Detection at point C, $d = |EC|$
  $x_0 = |CA|$

Two issues:

- Current of equilibrium charge carriers larger than excess carriers current
  ⇒ bias voltage applied at C, $\alpha V_b = \frac{x_0}{\ell} V_b$
  sign of both sweeping voltage V_s and bias voltage V_b determined by the type of minority carrier
- Joule heating of semiconductor bar
  ⇒ sweeping voltage applied in form of pulses with low duty-cycle

Current set-up



- Charge injection done using laser pulsed synchronised to sweeping field
- Sweeping pulse (~20 ns) larger than injection pulse

5. Theory

Charge carriers : force $F = eE$

$\Rightarrow \quad v = \mu E$

$\uparrow$ mobility

Random motion independent of E, in time t $\quad r \sim (Dt)^{1/2}$

$\uparrow$ diffusion constant

Brownian motion of classical particles : $\quad D = \dfrac{\mu k_B T}{e}$

$\uparrow$ Einstein relation

Excess carriers have average lifetime τ

Equation governing dynamics of excess minority carrier density $n(x,t)$

$$D \frac{\partial^2 n}{\partial x^2} - \mu E \frac{\partial n}{\partial x} - \frac{n}{\tau} = \frac{\partial n}{\partial t}$$

Solution : $\quad n(x,t) = \dfrac{A}{\sqrt{4\pi D t}} \exp\left(- \dfrac{(x - \mu E t)^2}{4Dt} - \dfrac{t}{\tau} \right)$

assuming at $t = 0$, $\quad \eta(x,0) = A\,\delta(x)$

$\uparrow$ delta function

Maximum at $x = d$, time t_0 :

$$\frac{\partial n(d,t)}{\partial t} = 0$$

$$\mu E = \left[\frac{d^2}{t_0^2} - \frac{2D}{t_0} \left(1 + \frac{2t_0}{\tau} \right) \right]^{1/2}$$

For $\dfrac{2Dt_0}{d^2}\left(1 + \dfrac{2t_0}{\tau}\right) \ll 1$, e.g. when $t_0 \lesssim \tau$ and $(Dt_0)^{1/2} \ll d$

$\Rightarrow$ meaning of these conditions ?

$$E = \frac{d}{\mu t_0} \left[1 - \frac{Dt_0}{d^2} \left(1 + \frac{2t_0}{\tau} \right) \right]$$

For large E, $\quad t_0 = \dfrac{d}{\mu E}$

Available Literature

- J.R. Haynes and W. Shockley, 1950, "The mobility and life of injected holes and electrons in Germanium" experiment first performed
- M. B. Prince, 1953 "Drift mobilities in Semiconductors. I. Germanium"
  1954 "Drift mobilities in Semiconductors. II. Silicon" experiment refined, precise measurements in wide temperature range
- J. P. McKelvin, 1955 "Diffusion effects in drift mobility measurements in Semiconductors" diffusion correction to eliminate systematic dependence on sweeping field

Day 1 22/03/2022

6. Measurements

Risk assessment

- Class 1 laser, if damaged becomes class 3
  ↑ attenuated
  ⇒ infrared, not visible light
- Voltage 50 V, not harmful ⇒ again if damaged can be higher
- Delicate fragile components, beware when changing sample
- Back posture, tired eyes

Setting up the equipment (oscilloscope)

- Trigger set on external source
- Large peak is normal carriers, smaller peak = minorities
- Delay in laser pulse to view minorities peak
- Acquire ⇒ average to stabilize signal

Calibration

- MOVE FIBRE switch : move glider to minimum distance, read d
- Compare reading to actual distance using caliper
  ⇒ if only using ruler $d = 2.0 \pm 0.5$ mm
  ⇒ with caliper $d = 1.79 \pm 0.05$ mm
- CALIBRATION swith : change to measured distance

⇒ We are currently using a Ge n-type sample

6.1. MEASURE MOBILITY μ

$$t_0 = \frac{d}{\mu E}$$

Set d, vary V_s

$$\frac{d}{t_0} = \mu \frac{V_s}{l}$$

l ← length semi conductor

t_0 ← time delay between trigger and peak (minorities detected)

- Put the trigger on 0 on x-axis (oscilloscope)
- Choose a voltage V_s
- Zoom unto the minority carrier peak, to see the difference in position of trigger and peak
- Set average to 128 to smooth curve
- Take snapshot and save data on USB

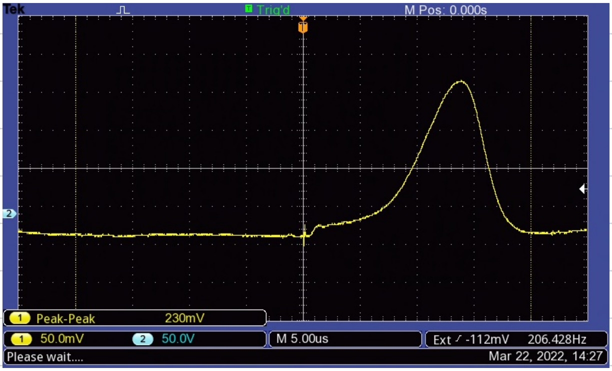
Values for V_s : 45.0V to 20.0V (15 V data not good)

uncertainty ± 0.1V

Measurement for l, $l = 2.0 \pm 0.1$ cm

↑ length of sample

Put both l and d in cm



Dataset 1

Fit linear (proportional) $y = mx$ function in Python

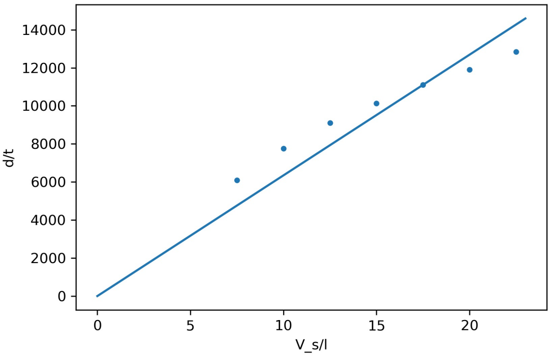
mobility $\mu = 628 \ cm^2/(Vs)$

Find maximum for each t_0 on .csv file

⇒ range of time where max voltage observed

⇒ take average of time range

→ plot Python



DAY 2 (24/03/2022)

Evaluate uncertainties on mobility

On y-axis $\frac{d}{t_0}$

$d = 1.79 \pm 0.05$ mm

For t_0 ⇒ value given by average of time range at max voltage

⇒ uncertainty taken as last time in range - first time

If only one time value corresponds to max ⇒ take oscilloscope time increment

$$y = \frac{d}{t_0}$$

$$\Rightarrow \Delta y = y \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta t_0}{t_0}\right)^2}$$

Chi-2 calculation $\chi^2 = \frac{(\text{observed} - \text{expected})^2}{\text{error}^2}$

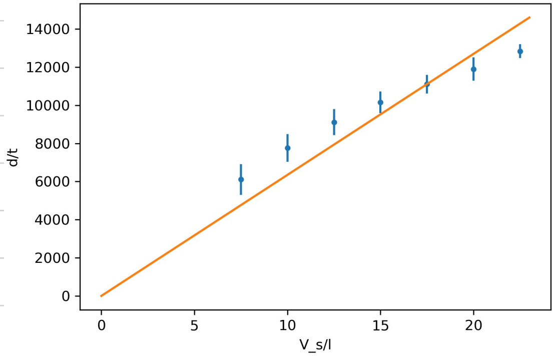
$$\chi^2_{red} = \frac{\chi^2}{N-1}$$

↑ 1 dof

Mobility : $\mu = 634 \pm 28$ $cm^2\ s^{-1}\ V^{-1}$

$\chi^2_{red} = 4.7$

↑ too high



$\Rightarrow$ Take more data to get a better idea and reduce χ^2

From 17V to 47V, in steps of 2V

$\Rightarrow$ 16 data points

$\boxed{\text{Dataset 2}}$

Python script

$\Rightarrow$ To automate the process of finding the maximum

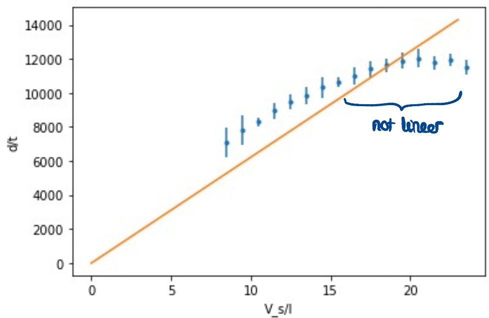
Iterates through all the files and extracts data

Finds the time range of max voltage

Takes average and calculates uncertainty

New data value : $\mu = 622 \pm 24 \ cm^2 s^{-1} V^{-1}$

with $\chi^2_{red} = 14.9$



$\Rightarrow$ Data does not seem linear

$$\frac{d}{t_0} = \mu \frac{V_s}{l}$$

1st order linear approximation

breaks down after 30 V

$\Rightarrow$ Full formula $\mu E = \left[\frac{d^2}{t_0^{\,2}} - \frac{2D}{t_0}\left(1 + \frac{2t_0}{\tau}\right)\right]^{1/2}$

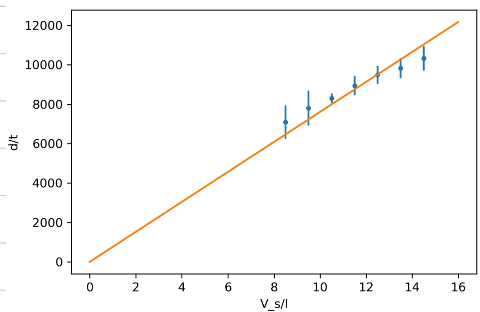
Plot only data between 17V and 29V

7 data points

$\mu = 761 \pm 16 \ cm^2 s^{-1} V^{-1}$

with $\chi^2_{red} = 0.80$

much better fit



6.2 Measure Diffusion Constant D

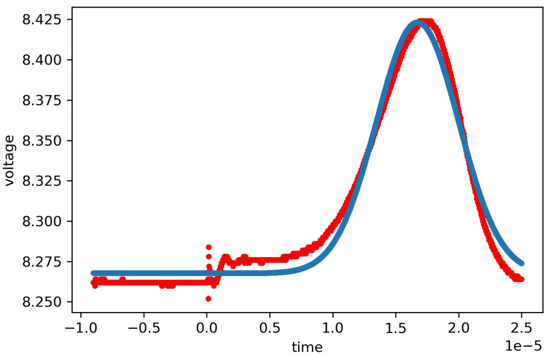
$$D = \frac{(t_p d)^2}{(16 \ln 2) t_0^3}$$

Assume shape of pulse is Gaussian, fit a Gaussian and find t_p

t_p : width at half maximum height

$t_p = 2\sqrt{2\ln 2}\,\sigma$ = fwhm

standard deviation



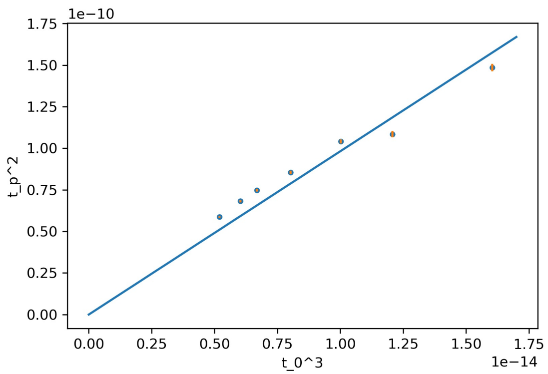
e.g Gaussian on right for 29V

Extract t_p

$$\Delta t_p = t_p \frac{\Delta\sigma}{\sigma}$$

Day 3 : 29/03/2022

Plot and linear fit t_p^2 against t_0^3



coefficient $m = 9820 \ s^{-1}$

$$m = \frac{16 D \ln 2}{d^2}$$

$\Rightarrow D = 28.4 \quad cm^2 s^{-1}$

Uncertainty on t_p^2

$$\Delta t_p = t_p \frac{\Delta\sigma}{\sigma}$$

$$\Delta(t_p^2) = \frac{\partial t_p^2}{\partial t_p} \Delta t_p$$

$$= 2 t_p \Delta t_p = 2 t_p^2 \frac{\Delta\sigma}{\sigma}$$

Uncertainty on t_p^2 too small $\Rightarrow$ additional source of uncertainty ?

↑ barely visible error bars

Idea: base of gaussian not at the same height on both sides

$\Rightarrow$ take height to estimate new error on σ

↑ standard deviation

Propagate uncertainties on D:

$$m = \frac{16 D \ln 2}{d^2}$$

$$\Rightarrow D = \frac{m d^2}{16 \ln 2}$$

$$\Delta D = D \sqrt{\left(2\frac{\Delta d}{d}\right)^2 + \left(2 \frac{\Delta m}{m}\right)^2}$$

Δm obtained from linear fit using curve fit

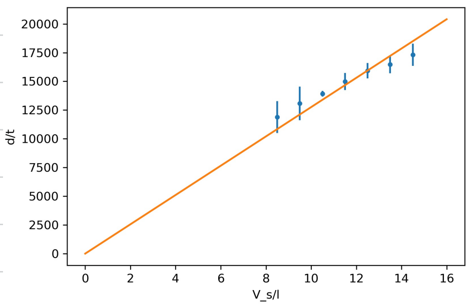
$D = 28 \pm 2 \quad cm^2\, s^{-1}$

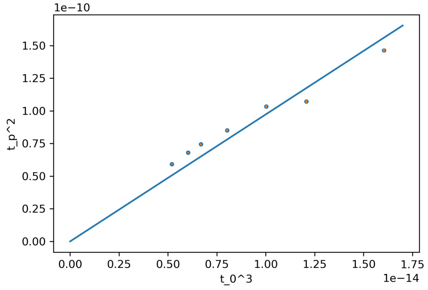
⚠ Mistake on our d value

→ we previously had not exactly measure distance between fibre and collection point

New value : $d = 3.00 \pm 0.05$ mm

↑ higher uncertainty ⇒ more difficult to measure due to proximity to fragile fibre





$\mu = 1275 \pm 27 \quad cm^2\, V^{-1}\, s^{-1}$

$\chi^2_{red} = 1.3$

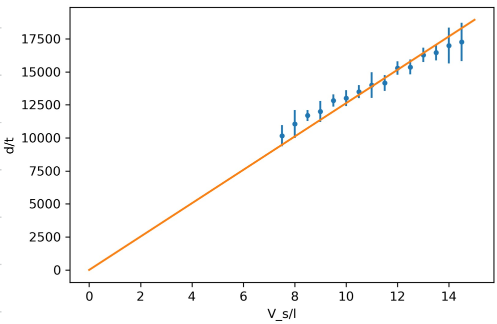
$D = 79 \pm 4 \quad cm^2\, s^{-1}$

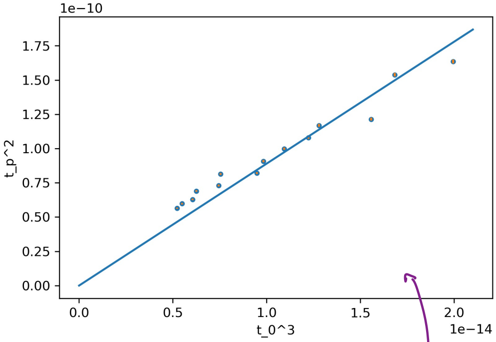
Dataset 3

New set of measurements trigger -20 μs

			file	volt	
0:	50	50mV vertical, time 5μs			
1 :	49		25	26V	change in vertical scaling to 20 mV
2 :	48		26	25V	
3 :	47		27	24V	
4 :	46		28	23V	
5 :	45		29	22V	
6 :	44		30	21V	
7 :	43		31	20V	
8 :	42		32	19V	
9 :	41		33	18V	
10 :	40		34	17V	
12 :	39	* skip	36	16V	* skip, time step 10 μs
13 :	38		37	15V	
14 :	37		38	14V	
15 :	36		39	13V	
16 :	35		40	12V	
17 :	34				
18 :	33				
19 :	32				
20 :	31				
21 :	30				
22 :	29				
23 :	28				
24:	27 V				

Day 4 (31/03/2022)





$\mu = 1263 \pm 15 \quad cm^2 s^{-1} V^{-1}$

$\chi^2_{red} = 1.04$

Data between 15 and 29V

$D = 72 \pm 5 \quad cm^2 s^{-1}$

Very small error bars $\chi^2_{red} \approx 200$

Statistically, larger error bars do not change the uncertainty on D, since curve fit minimises R^2, not χ^2

↑ do not take uncertainties into account

6.3 Measure Lifetime τ

$$n(x,t) = \frac{A}{\sqrt{4\pi D t}} \exp\left(- \frac{(x-\mu E t)^2}{4Dt} - \frac{t}{\tau}\right)$$

at $x = d = \mu E t$

$$n_0 = \frac{A}{\sqrt{4\pi D t_0}} \exp\left(- \frac{t_0}{\tau}\right)$$

$$n_0 \sqrt{t_0} = \frac{A}{\sqrt{4\pi D}} \exp\left(- \frac{t_0}{\tau}\right)$$

$$\ln n_0 \sqrt{t_0} = \ln \frac{A}{\sqrt{4\pi D}} - \frac{t_0}{\tau}$$

n_0 : height of pulse in V

t_0 : delay in s

Uncertainties on y - axis : $\ln n_0 \sqrt{t_0}$

$$\Delta n_y^2 = \left(\frac{\partial n_y}{\partial t_0}\right)^2 \Delta t_0^2 + \left(\frac{\partial n_y}{\partial n_0}\right)^2 \Delta n_0^2$$

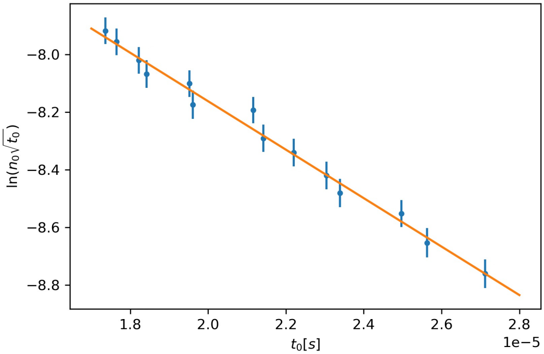
$$= \left(\frac{n_0 \frac{\partial}{\partial t_0} \sqrt{t_0}}{n_0 \sqrt{t_0}}\right)^2 \Delta t_0^2 + \left(\frac{1}{n_0}\right)^2 \Delta n_0^2$$

$$= \left(\frac{\frac{1}{2} t_0^{-1/2}}{t_0^{1/2}}\right)^2 \Delta t_0^2 + \frac{\Delta n_0^2}{n_0^2}$$

$$= \left(\frac{1}{2t_0}\right)^2 \Delta t_0^2 + \frac{\Delta n_0^2}{n_0^2}$$

$$= \frac{1}{4} \frac{\Delta t_0^2}{t_0^2} + \frac{\Delta n_0^2}{n_0^2}$$

$$\Delta n_y = \sqrt{\left(\frac{\Delta t_0}{2t_0}\right)^2 + \left(\frac{\Delta n_0}{n_0}\right)^2}$$



Value for τ : $\tau = 11.9 \pm 0.4$ µs

$\chi^2_{red} = 0.42$

slope $= -\frac{1}{\tau} = m$

Change uncertainties t_0 : took σ from gaussian fit / 2

$\tau = \frac{-1}{m}$

$\Delta\tau^2 = \left(\frac{\partial\tau}{\partial m}\right)^2 \Delta m^2$

$= \left(\frac{1}{m^2}\right)^2 \Delta m^2$

$= \tau^2 \frac{\Delta m^2}{m^2}$ $\qquad \Delta\tau = \tau \frac{\Delta m}{m}$

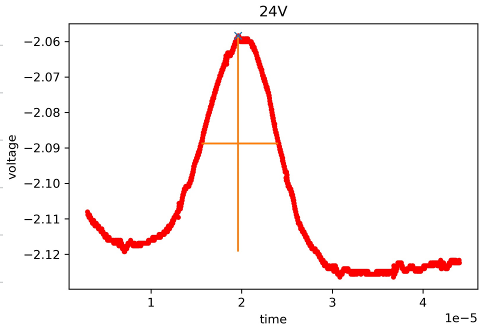
Day 5 (26/04/2022)

Determine uncertainties on t_0 and t_p by taking 5 sets of measurements

$\Rightarrow$ statistical uncertainties

$\Rightarrow$ take standard deviation

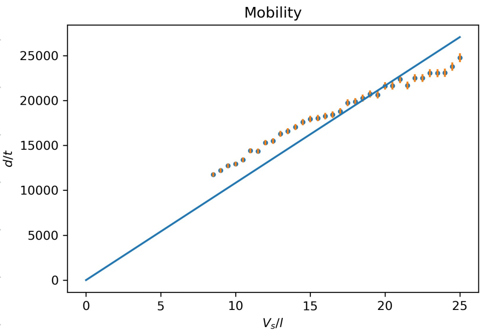
Also, use find_peaks on Python to find t_0, n_0 and t_p faster

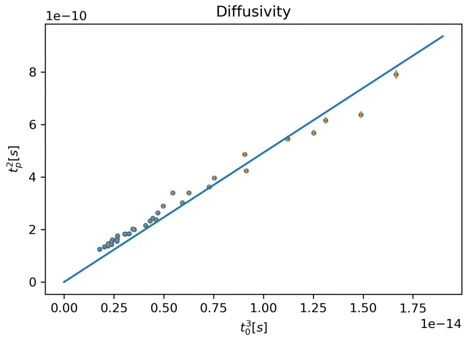


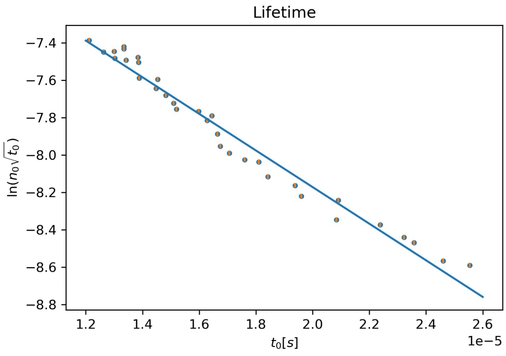
We did this on 3 values: 17V, 20V, 23V

6 measurements taken: on t_0, n_0 and t_p, ~ 1% uncertainty

Plots for lifetime, diffusion and mobility







Current values :

$\mu = 1082 \pm 18$ $cm^2 s^{-1} V^{-1}$

$D = 400 \pm 15$ $cm^2 s^{-1}$

$\tau = 10.2 \pm 0.3$ μs

For mobility $\Rightarrow$ will compare with full model

some values must be cut-off $\Rightarrow$ linear approximation seems to fail at higher V

$\Rightarrow$ evaluate systematic uncertainties depending on where we cut off

4.4 VARYING d

For mobility, $$\frac{d}{t_0} = \mu \frac{V_s}{l}$$

$$\frac{1}{t_0} = \mu \frac{V_s}{l d}$$

$$\frac{l}{t_0} = \mu \frac{V_s}{d}$$

$\boxed{\text{Dataset 4}}$ $V_s = 25.0 \pm 0.1\,V$, d varies between 3.0 and 5.5 mm

For diffusion, $$D = \frac{(t_p d)^2}{16 \ln 2\, t_0^3}$$

$$\frac{1}{(t_p d)^2} = \frac{1}{D} \frac{1}{16 \ln 2\, t_0^3}$$

$$(t_p d)^2 = 16 \ln 2\, D \quad t_0^3$$

$$y = (t_p d)^2$$

$$\Delta y^2 = \left[\left(\frac{\partial y}{\partial t_p}\right)^2 \Delta t_p^2 + \left(\frac{\partial y}{\partial d}\right)^2 \Delta d^2 \right]$$

$$= \left[(2 t_p d^2)^2 \Delta t_p^2 + (2 d t_p^2) \Delta d^2 \right]$$

$$= \left[\left(2 \frac{y}{t_p}\right)^2 \Delta t_p^2 + \left(2 \frac{y}{d}\right)^2 \Delta d^2 \right]$$

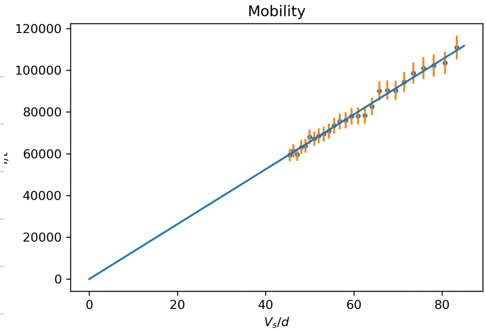
$$= y^2 \left[4 \left(\frac{\Delta t_p}{t_p}\right)^2 + 4 \left(\frac{\Delta d}{d}\right)^2 \right]$$

$$\Delta y = 2y \sqrt{\left(\frac{\Delta t_p}{t_p}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$

For lifetime, same as before:

$$\ln\left(\sqrt{t_0}\, n_0\right) = \ln\left(\frac{A}{\sqrt{4\pi D}}\right) - \frac{t_0}{\tau}$$

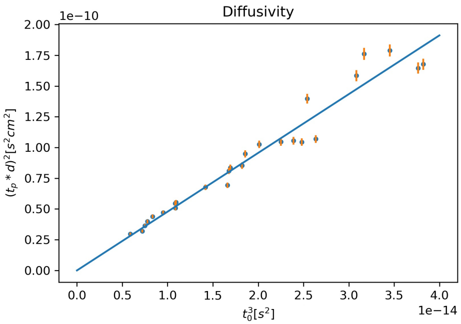
$$\Delta y = \sqrt{\left(\frac{\Delta t_0}{2 t_0}\right)^2 + \left(\frac{\Delta n_0}{n_0}\right)^2}$$



Mobility data much more satisfactory

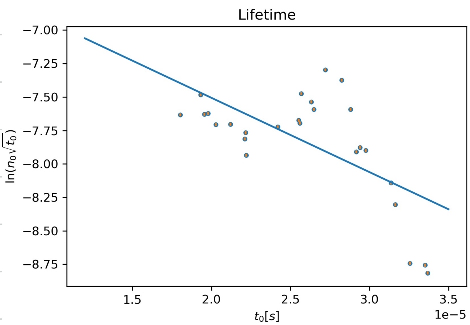
⇒ we can clearly see the linear dependence

$\mu = 1313 \pm 5 \quad cm^2 s^{-1} V^{-1}$



Good as well.

$D = 431 \pm 8 \quad cm^2 s^{-1}$



Here there was a problem

1st data set taken by varying d, noisy data

We cannot see a linear relation

⇒ take new data set

⇒ could also try plotting area instead of n_0

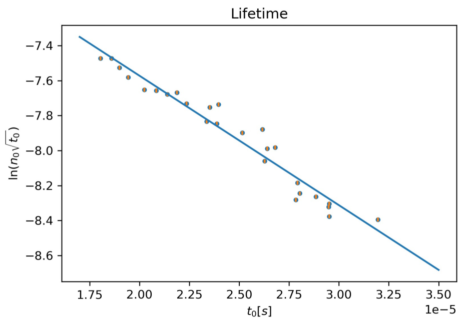
area $= n_0 t_p$

Day 6

Aims : - Obtain plot for lifetime
- Apply correction on varying voltage correction
- Work on removing background

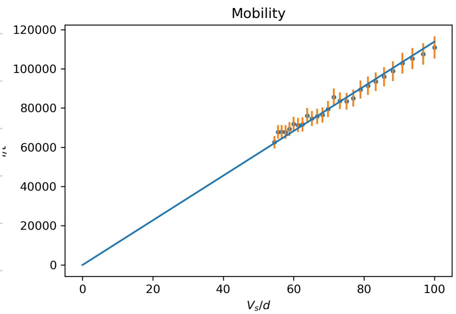
$\boxed{\text{Dataset 5}}$ new data varying d.

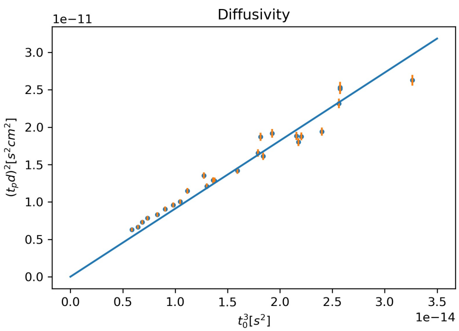
⇒ more careful about stabilising signal



much better data, apparent linear relation

$\tau = 17 \pm 1$ μs

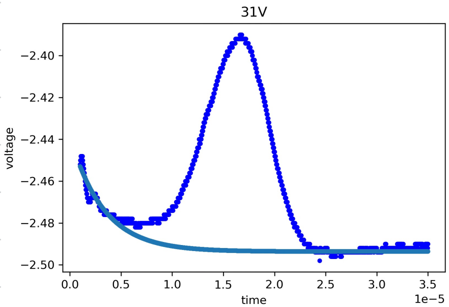




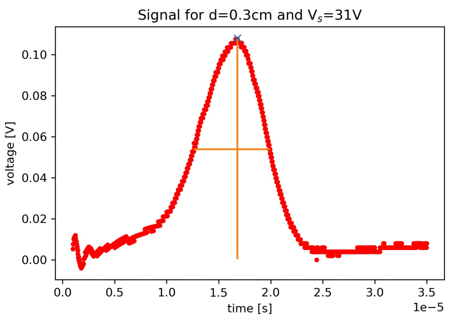
Background Substraction

How to substract the background from the signal peak?

- Remove peak from volt data (y-axis), so that there is a smooth decreasing curve for the background
- Fit an exponential to it
- Substract this fitted exponential from full data set



This shows the fitted exponential in light blue (fitted using curve fit)



We find the peak and full width half maximum using find_peaks.

5.5 CORRECTION ON MOBILITY μ

Continuity equation :

$$\frac{\partial \rho}{\partial t} = \underline{\nabla} \cdot (D \underline{\nabla} \rho) - \mu \underline{E} \cdot \underline{\nabla} \rho - \frac{\rho}{\tau}$$

Solution : $\rho(x,t) = \frac{N}{(4\pi D t)^{1/2}} \exp\left(-\frac{(x-\mu E_0 t)^2}{4Dt} - \frac{t}{\tau}\right)$

for a number of N minority carriers injected simultaneously at $t=0$ at the origin

If instead, a number of carriers dN are injected in an interval dt at $t=0$, and this rate is maintained for time t

$\Rightarrow$ superposition of solutions like above

$$\rho(x,t) = \int_0^t \rho(x,t) = N \int_0^t \frac{1}{(4\pi D t)^{1/2}} \exp\left[-\frac{(x-\mu E_0 t')^2}{4Dt'} - \frac{t'}{\tau}\right] dt'$$

Set $x = d$, and use Einstein relation $\frac{D}{\mu} = \frac{k_B T}{e}$ to remove μ

$$\mu = \frac{eD}{k_B T}$$

$$\frac{d^2}{4Dt'} + \alpha t' = \frac{d^2}{4Dt'} + \frac{\mu e E_0^2}{4kT} t' + \frac{t'}{\tau}$$

$$= \frac{d^2 + \frac{\mu e E_0^2 D t'^2}{kT}}{4Dt'} + \frac{t'}{\tau}$$

$$= \frac{d^2 + (\mu E_0 t')^2}{4Dt'} + \frac{t'}{\tau} \approx \frac{(d - \mu E_0 t')^2}{4Dt'} + \frac{t'}{\tau}$$

We can set $\left.\frac{d^2 \rho}{dt^2}\right|_{t=t_0} = 0$

transit time t_0 = interval between injection at $t=0$ and the time where the inflection point of the arrival curve occurs

1st derivative removes integral

2nd derivative: $t_0 = \frac{1}{4\alpha}\left[\left(1 + \frac{4\alpha d^2}{D}\right)^{1/2} - 1\right]$

Sub $\alpha = \frac{\mu e E_0^2}{4kT} + \frac{1}{\tau}$ in, we get

$\Rightarrow \mu = \mu_0\left[(1+x^2)^{1/2} - x\right]$, where $x = \frac{2kT}{eE_0 d}\left(\frac{t_0}{\tau} + \frac{1}{2}\right)$

and $\mu_0 = \frac{d}{t_0 E_0}$

The actual mobility differs from μ_0 by factor depending on E_0 and τ, which may be large for small E_0.

On $\boxed{\text{Dataset 3}}$

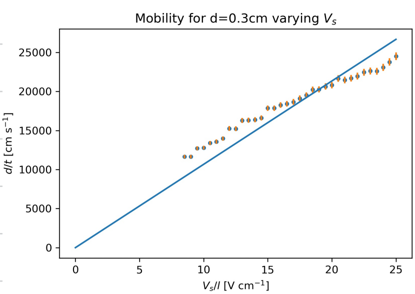
Large dispersion in mobility values, between 1000 and 1400 $cm^2 s^{-1} V^{-1}$

average value = 1128 $cm^2 s^{-1} V^{-1}$

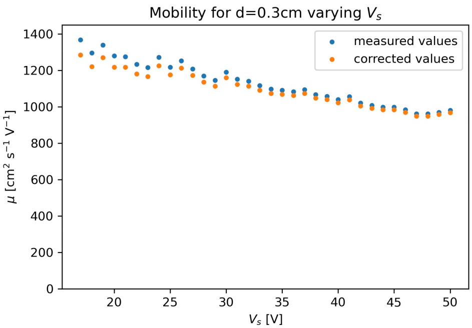
$\Rightarrow$ systematic dependence on sweep voltage V_s

This is due to diffusion and recombination of excess carriers

effect becomes more important at lower sweeping voltage V_s

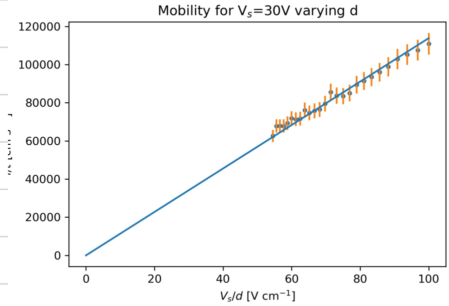


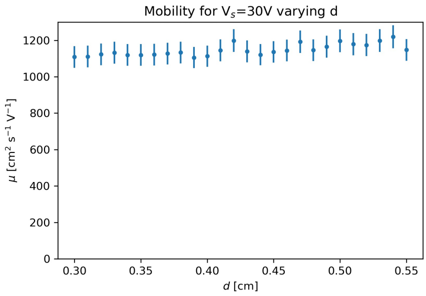
On this graph, we can see relation is not a linear one



This plot shows there is not one value for mobility, but a range between 1400 - 1000
Applying correction reduces range

This is not an issue when we vary d





↑ linear relation

↑ horizontal line

Einstein Relation

Einstein relation : $\frac{D}{\mu} = \frac{k_B T}{e}$

For Dataset 3 varying V_s : $\frac{D}{\mu} = 0.067 \pm 0.003$ V

For Dataset 5 varying d : $\frac{D}{\mu} = 0.072 \pm 0.001$ V

Results

$\boxed{\text{Dataset 3}}$

$\mu = 1067 \pm 17 \ cm^2 \ s^{-1} V^{-1}$ $\neq$ $\mu = 1096 \pm 99 \ cm^2 \ s^{-1} V^{-1}$

↑ taking average and standard deviation of corrected values

$D = 76 \pm 3 \ cm^2 \ s^{-1}$

$\tau = 9.8 \pm 0.2 \ \mu s$

$\boxed{\text{Dataset 5}}$

$\mu = 1138 \pm 6 \ cm^2 \ s^{-1} V^{-1}$

$D = 82 \pm 1 \ cm^2 s^{-1}$

$\tau = 13.5 \pm 0.6 \ \mu s$

Day 7 (03/05/2022)

Aims : - take data on new sample

- exponential non-linear fit of equation 1

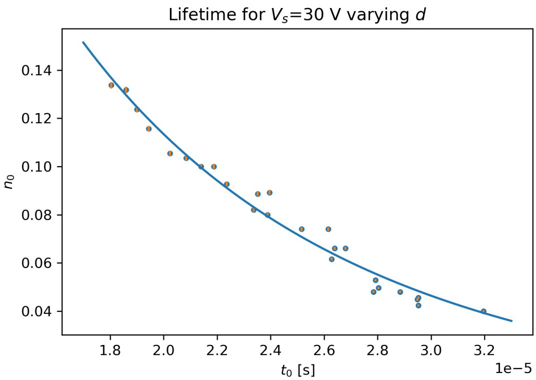
6.6 Non-Linear Fit for Lifetime

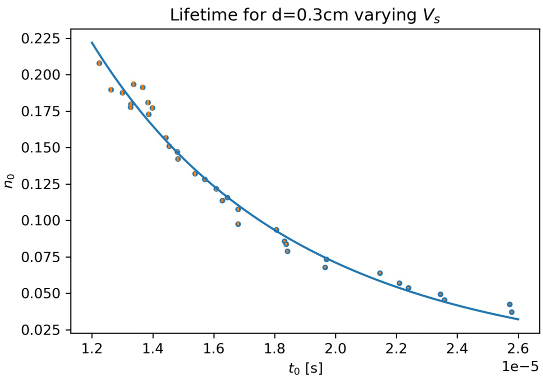
$$n_0 = \frac{A}{\sqrt{4\pi D}} \exp\left(-\frac{t_0}{\tau}\right) \frac{1}{\sqrt{t_0}}$$

Fitted function: exponential $\times$ $\frac{1}{\text{square root}}$

Dataset 3 $\tau = 9.1 \pm 0.3$ μs

Dataset 5 $\tau = 14.5 \pm 0.7$ μs



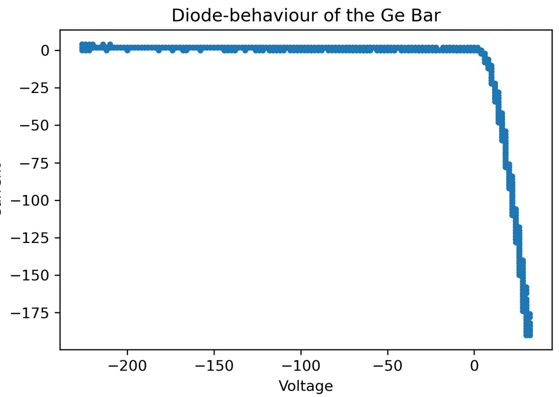


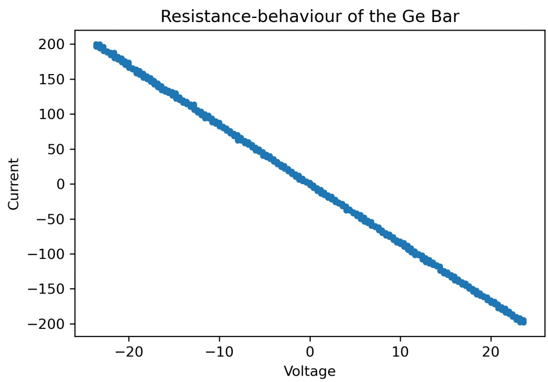
Measurement Resistance and Diode Behaviour of Ge Bar

x : white cable, channel 1 : current I

y : black cable, channel 2 : voltage V

Plot current against voltage





Plots are mirrored compared to what they should be

⇒ we're looking at the minority carriers and not majority carriers

New data : $\boxed{\text{Dataset 7}}$ vary V } on new sample
$\boxed{\text{Dataset 8}}$ vary d

$\boxed{\text{Dataset 7}}$ From 50V to 17V, in increments of 1V , d = 3.0 mm

$\boxed{\text{Dataset 8}}$ From 3.0mm to 5.0mm, in increments of 0.1mm , V = 30V

0 :	3.0mm	12	4.2m
1 :	3.1mm	13	4.3mm
2 :	3.2mm	14	4.4mm
3 :	3.3mm	15	4.5mm
4 :	3.4mm	16	4.6mm
5 :	3.5mm	17	4.7mm
6 :	3.6mm	18	4.8mm
7 :	3.7mm	19	4.9mm
8 :	3.8mm	20	5.0mm
9 :	3.9mm		
10 :	4.0mm		
11 :	4.1mm		

$\boxed{\text{Dataset 6}}$ other pair's data
⇒ not good quality , we decided to take our own

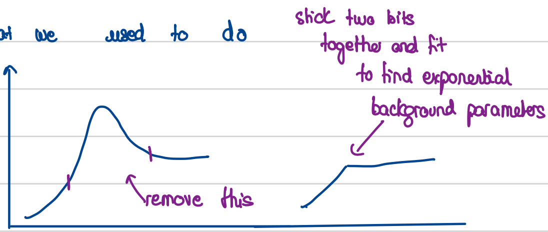
Day 8 (05/05/2022)

Analyse $\boxed{\text{Dataset 7}}$ and $\boxed{\text{Dataset 8}}$

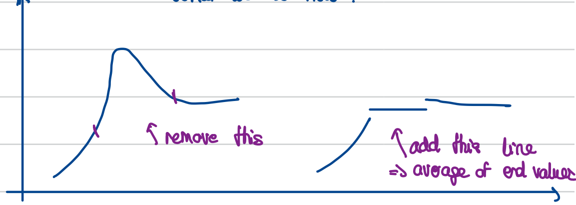
- background substraction ⇒ function fitted exponential, but often looks linear on graphs

⇒ improvement on background fitting method, since ours did not work on strong steep backgrounds like we had on this new sample

What we used to do



What we do now :

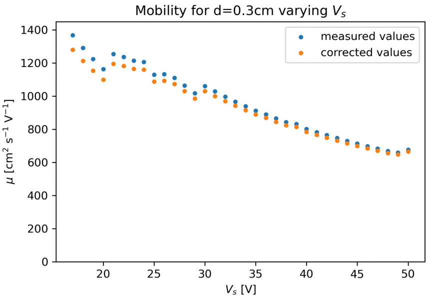


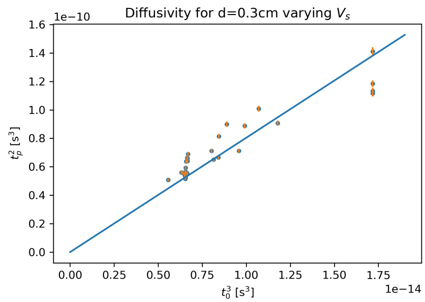
$\boxed{\text{Dataset 7}}$ (vary V)

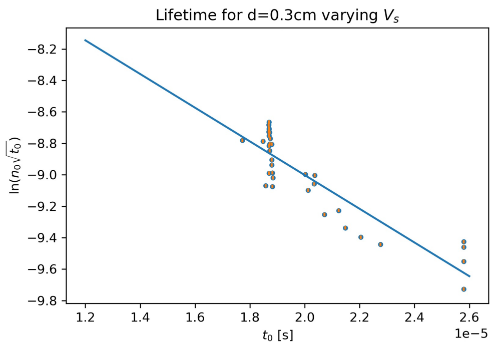
$\mu = 927 \pm 189 \ cm^2 s^{-1} V^{-1}$

$D = 68 \pm 3 \ cm^2 s^{-1}$

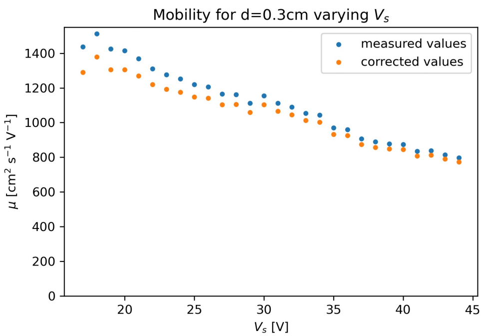
$\tau = 9.3 \pm 0.8 \ s$ ✗ no

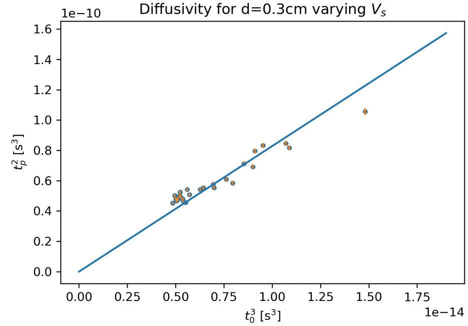






Dataset 9 — new data varying V, to try to get a better mobility value



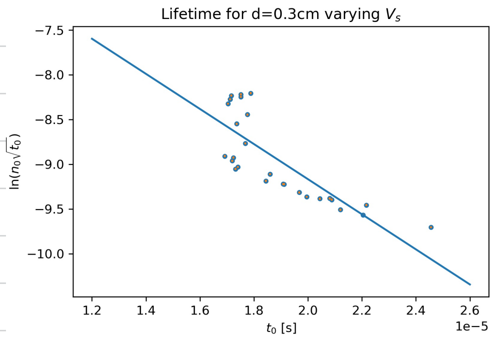


$\mu = 1050 \pm 178 \quad cm^2 s^{-1} V^{-1}$

$D = 67 \pm 3 \quad cm^2 s^{-1}$

$\tau = 5.1 \pm 0.7 \quad \mu s$

↑ lifetime plot not satisfactory



Method update : go back to using gaussians instead of find peaks

For $\boxed{\text{Dataset 8}}$ vary d

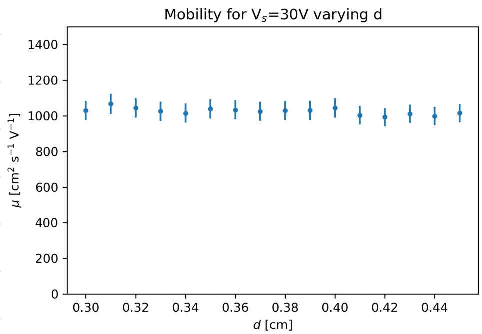
$\mu = 1029 \pm 5 \quad cm^2\, s^{-1} V^{-1}$

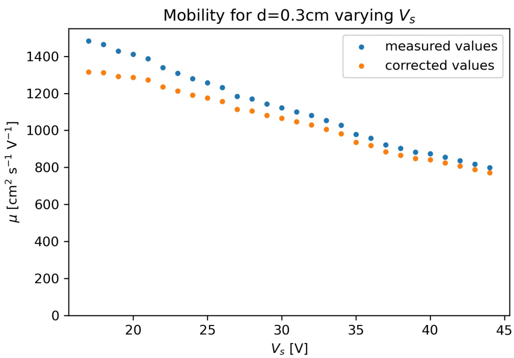
$D = 72 \pm 3 \quad cm^2\, s^{-1}$

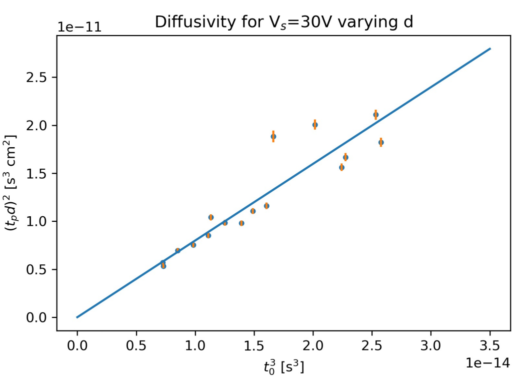
For $\boxed{\text{Dataset 9}}$ vary V

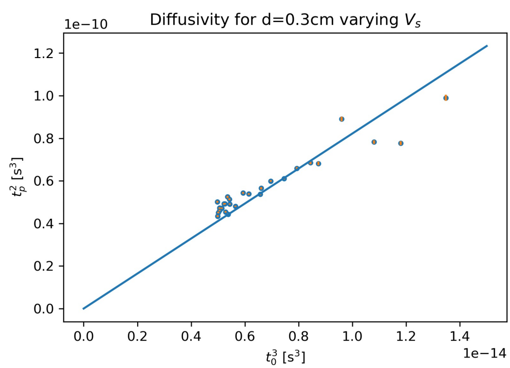
$\mu = 1049 \pm 175 \quad cm^2\, s^{-1} V^{-1}$

$D = 67 \pm 3 \quad cm^2\, s^{-1}$









EQUATION (1) FIT

Using Equation (1) lab script

$$n(x,t) = \frac{A}{\sqrt{4\pi D t}} \exp\left(-\frac{(x-\mu E t)^2}{4Dt} - \frac{t}{\tau}\right)$$

When we fit gaussian, we approximate $\sqrt{Dt} \ll d$ and $t_0 \sim \tau$

so $n(x,t) = a \exp\left(-\frac{(x-b)^2}{2c^2}\right)$

In (1) for $x=d$: $\frac{(d-\mu E t)^2}{4Dt} = \frac{(\mu E)^2 \left(t - \frac{d}{\mu E}\right)^2}{4Dt}$, $\mu E = \frac{d}{t_0}$

$$= \frac{\left(t - \frac{d}{\mu E}\right)^2}{4Dt_0 \left(\frac{t_0}{d}\right)^2}$$

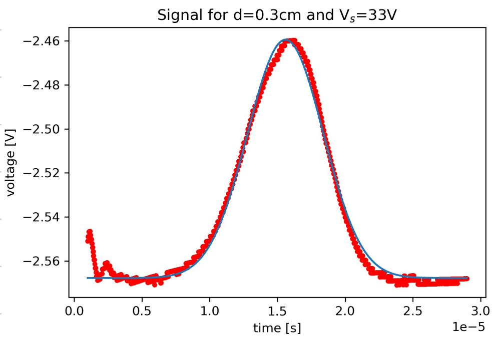
$$\text{“} \quad 4 \frac{\cancel{t_0^3}}{\cancel{d^2}} \frac{t_p^2 \cancel{d^2}}{16 \ln 2 \, \cancel{t_0^3}} = \frac{t_p^2}{4 \ln 2} \quad , \quad t_p = 2\sqrt{2 \ln 2}\,\sigma$$

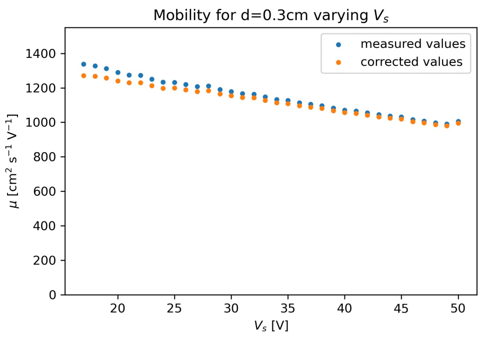
$$= \frac{4 \cdot 2\ln 2 \, \sigma^2}{4 \ln} = 2\sigma^2$$

$\Rightarrow$ we get back Gaussian form

Fit full model

$\mu = 1122 \pm 89 \ cm^2 s^{-1} V^{-1}$





Summary

	1st sample	2nd sample
Varying V	$\boxed{\text{Dataset } 3}$	$\boxed{\text{Dataset } 9}$
	$\mu = 1132 \pm 86 \ cm^2 s^{-1} V^{-1}$	$\mu = 1007 \pm 154 \ cm^2 s^{-1} V^{-1}$
	$D = 73 \pm 3 \ cm^2 s^{-1}$	$D = 67 \pm 3 \ cm^2 s^{-1}$
	$\tau = 9.0 \pm 0.3 \ \mu s$	$\tau = 2.5 \pm 0.5 \ \mu s$
Varying d	$\boxed{\text{Dataset } 5}$	$\boxed{\text{Dataset } 8}$
	$\mu = 1177 \pm 4 \ cm^2 s^{-1} V^{-1}$	$\mu = 1032 \pm 5 \ cm^2 s^{-1} V^{-1}$
non linear fit	$D = 92 \pm 1 \ cm^2 s^{-1}$	$D = 72 \pm 3 \ cm^2 s^{-1}$
	$\tau = 15.1 \pm 0.8 \ \mu s$	$\tau = 16 \pm 6 \ \mu s$

gaussian fits

$\Rightarrow$ $\mu = 1155 \pm 32 \ cm^2 s^{-1} V^{-1}$

$D = 83 \pm 13 \ cm^2 s^{-1}$

$\tau = 12 \pm 4 \ \mu s$

$\Rightarrow$ $\mu = 1020 \ cm^2 s^{-1} V^{-1}$

$D = 70 \pm 4 \ cm^2 s^{-1}$

$\tau = 9 \pm 10 \ \mu s$