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First Working Group Meeting on the Minority Carrier Diffusion Length/ Lifetime Measurement

Results of the Round Robin Lifetime/ Diffusion Length Tests

Meeting Chairman: B. Sopori

Compiled by: M. Cudzinovic and B. Sopori

December 18–19, 1993
Scottsdale, Arizona

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November 1995

RESULTS OF THE ROUND ROBIN LIFETIME/DIFFUSION LENGTH TESTS

Results of the Round Robin Lifetime/Diffusion Length Tests

At the first working group meeting on the measurement of minority carrier lifetime/diffusion length (τ/L), held in Scottsdale, Dec. 1993, it was decided to have a round robin activity using selected wafers and cells. Accordingly, samples of wafers and solar cells from various vendors were collected and circulated among the participants. It took a while (two years) but, the results are finally here.

Michael Cudzinovic has been kind enough to volunteer to send samples to different laboratories, to "bug" people when he got somewhat desperate, and to send a copy of the test data to the participants (attached). Also attached are: a summary of data, the sample coding scheme, and the names of the persons who were responsible for having the measurements done. Please go through these data, maybe talk to the folks if your data does not match with others, and please give me some feedback as to what we should do next. It is clear from the results that

1. Diffusion length measurements are fairly close (except NREL's results are too low for longer diffusion length values).
2. Lifetime results from MIT are generally higher than NCSU; results from Mobil (now ASE) are probably closer to MIT than to NCSU.
3. Results of mapping by USF show that the standard deviations of the values over the entire sample are relatively small.
4. There is good agreement of diffusion length measurements on finished cells.

These results indicate some concerns that we need to address, perhaps at a second meeting. In addition, we also need to address how recommended procedure could be followed in making the measurements. For example, it was not possible for all parties to keep the illumination levels same (even though it was thought to be important at the meeting). Secondly, this set of samples did not show a large variation within a sample. Hence, the question of "average" values and their usefulness remains to be resolved.

I think it was a good beginning and that this effort by participants is very valuable. Perhaps we need to have another meeting that could address the following issues:

- Sources of variations from lab to lab.
- Is there any point in making a single (or a few) measurement(s) on a non-uniform wafer or cell, and what does it tell us?
- How meaningful are diffusion length values in predicting the cell performance?

I should also like to point out that there is some work being done in parallel (which many of you will or have already discussed) wherein we will make τ/L measurements of samples after various process steps and fabricate cells with different processes. But the emphasis of that project is not as detailed on these measurements; all the same these data can also be helpful.

Finally, I would like to thank all of you for participating in this exercise, and I hope the next go around will take much less time.

Summary of Diffusion Length and Lifetime Data on Bare Silicon

As was noted in the cover letter that accompanied the samples, the eleven bare silicon samples were from various manufacturers. Table I lists the codes for the samples and the manufacturer of each sample. It also notes if the sample was single or poly-crystalline. The samples had been polished on one side before being sent out for measurements, but no further processing was done.

The participants of the study were asked to measure either the lifetime or diffusion length of each of the samples using their standard procedure. Table II shows the experimental conditions used by the groups who measured diffusion length. All the diffusion length measurements were performed using the Surface Photovoltage method (SPV). Table III shows the experimental conditions for the lifetime measurements. All the lifetime measurements were made using the Photoconductance Decay method (PCD) under low level injection. These tables show the diameter of the spot size used during the measurement (the effective sampling area), the locations where measurements were taken, and the number of measurements taken at each location.

Table IV shows the results of the measurements. The table is divided into diffusion length and lifetime measurements for each sample. The values listed are the average values reported by each group.

One of the immediate artifacts seen in the data is the large variation in the lifetime measurements. The values from MIT and Mobil are generally close. However, the measurements from NCSU are typically an order of magnitude lower. The diffusion length measurements have much less scatter. There is still a factor of two difference in some values, but the overall agreement is much better.

At the Working Group Meeting there was concern that care needed to be taken to ensure that each of the groups measure the same location on the samples, preferably the exact same grain. However, the variation from grain to grain appears to be much less of a concern than the variation between groups. Samples 1SB, 10SB, and 11SB are all single crystal, yet the diffusion length values vary by as large as a factor of two and the lifetime values all vary by an order of magnitude. The measurements by USF provides some insight to the grain variations; the small spot size allows them to measure single grains. Figure 1 shows the average diffusion length and standard deviation for each of the samples. The standard deviations are typically less than the variations between different groups.

Summary of Diffusion Length Data on Finished Silicon Cells

The finished cells consisted of six 1 cm^2 multicrystalline silicon cells fabricated at Georgia Institute of Technology and six 4 cm^2 single crystal cells on three 10 cm diameter wafers fabricated at Sandia National Laboratories. Table V lists the sample codes and who did the manufacturing. Table VI shows the measured diffusion length values. Three groups measured the cells: Georgia Institute of Technology (GIT), Sandia National Laboratories (SNL), and Netherlands Energy Research Foundation (ECN). GIT and SNL measured diffusion length through Internal Quantum Efficiency. ECN measured lifetime by Light Beam Induced Current Decay and then calculated diffusion length. ECN's diffusion length values are shown in Table VI for more direct comparison with the other groups. ECN also calculated diffusion length for various wavelengths and with and without light bias. An average of the light bias values is shown in Table VI. There is generally good agreement between groups for the L values.

Sample Code	Manufacturer	Crystal Structure
1SB	MEMC	single
2SB	AstroPower	poly
3SB	Mobil (polished)	poly
4SB	OTC Magnetic	poly
5SB	Siemens	single
6SB	Mobil (unpolished)	poly
7SB	Solarex	poly
8SB	OTC Standard	poly
9SB	Crystal Systems	poly
10SB	Wacker	single
11SB	PCA	single

Table I: Manufacturers of the various samples used; referenced by sample number. The crystal structure denotes if the sample was single or poly-crystalline.

Group Name:	USF	NREL	MEMC
Spot Size:	1 mm	1.0 cm	0.5 cm
Measurement Locations:	mapped sample	center and edges	center
# Measurement/Location	1	2	5

Table II: Experimental conditions used by the groups who measured diffusion length. All measurements were done using SPV. The locations they measured and the number of measurements made at each locations is also listed.

Group Code:	MIT	Mobil	NCSU
Spot Size:	entire wafer		
Measurement Locations:		center	various
# Measurement/Location:	64	1	1

Table III: Experimental conditions used by the groups who measured lifetime. All measurements were done using PCD under low injection levels. The locations they measured and the number of measurements made at each locations is also listed.

Sample Code	Diffusion Length Measurements (all SPV) in µm			Lifetime Measurements (all PCD) in µs		
	USF	NREL	MEMC	MIT	Mobil	NCSU
1SB	216	108	248	33	64	1.64
2SB	6.7	8.1	6.8	50.4	1.2-43	-
3SB	14.4	29	28.6	<1	0.75	1.57
4SB	61.3	80	80	20.3	11	1.25
5SB	84.9	62	96	<1	17	2.08
6SB	20.4	36	21	<1	0.6	<0.3
7SB	59.8	96	77	15.4	11	1.87
8SB	90	94	100	25.8	17	0.85
9SB	35.4	31	41	2.7	1.0	1.63
10SB	120	96	134	20.3	45	<0.3
11SB	126	96	144	16.9	55-83	1.82

Table IV: Compilation of the results of the measurements. All the diffusion length values are in µm; all the lifetime values are in µs.

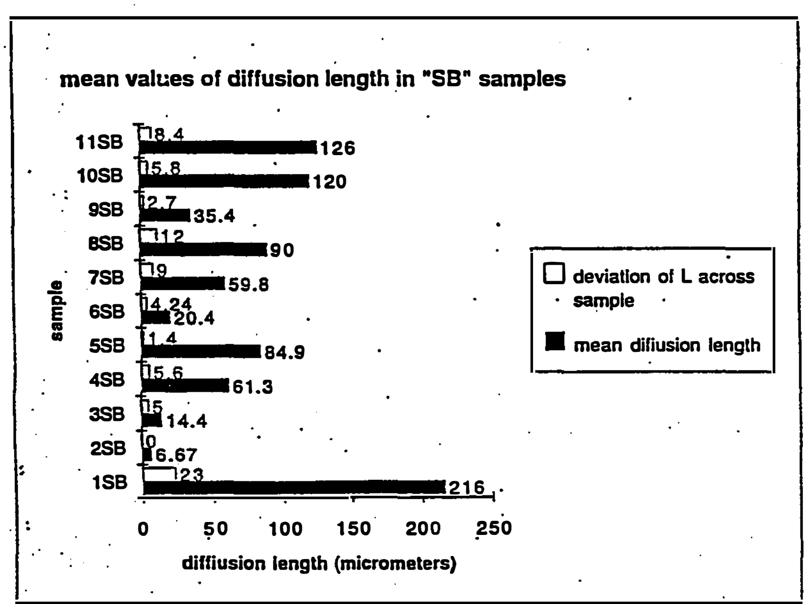


Figure 1: Average diffusion length and deviation as measured by USF. Note that the deviation is less than the variation in values between groups.

Sample Code	Where Fabricated
1CB	GIT (poly)
2CB	GIT (poly)
3CB	GIT (poly)
4CB	GIT (poly)
5Cb	GIT (poly)
6CB	GIT (poly)
7CB-D	SNL (single)
7CB-E	SNL (single)
8CB-D	SNL (single)
8CB-E	SNL (single)
9CB-D	SNL (single)
9CB-E	SNL (single)

Table V: Sample codes for finished cells and where cells were fabricated (GIT=Georgia Institute of Technology, SNL= Sandia National Laboratories). 7CB-D and 7CB-E are the two middle cells on a 10 cm diameter single crystal wafer. The same for 8CB and 9CB.

Sample Code	GIT (IQE)	SNL(IQE)	ECN (LBICD)
1CB	158	165	
2CB	138	195	
3CB	218	-	
4CB	273	-	
5Cb	-	215	
6CB	258	270	
7CB-D	625	510	360
7CB-E	-	500	355
8CB-D	590	390	344
8CB-E	-	350	335
9CB-D	298	220	231
9CB-E	-	230	233

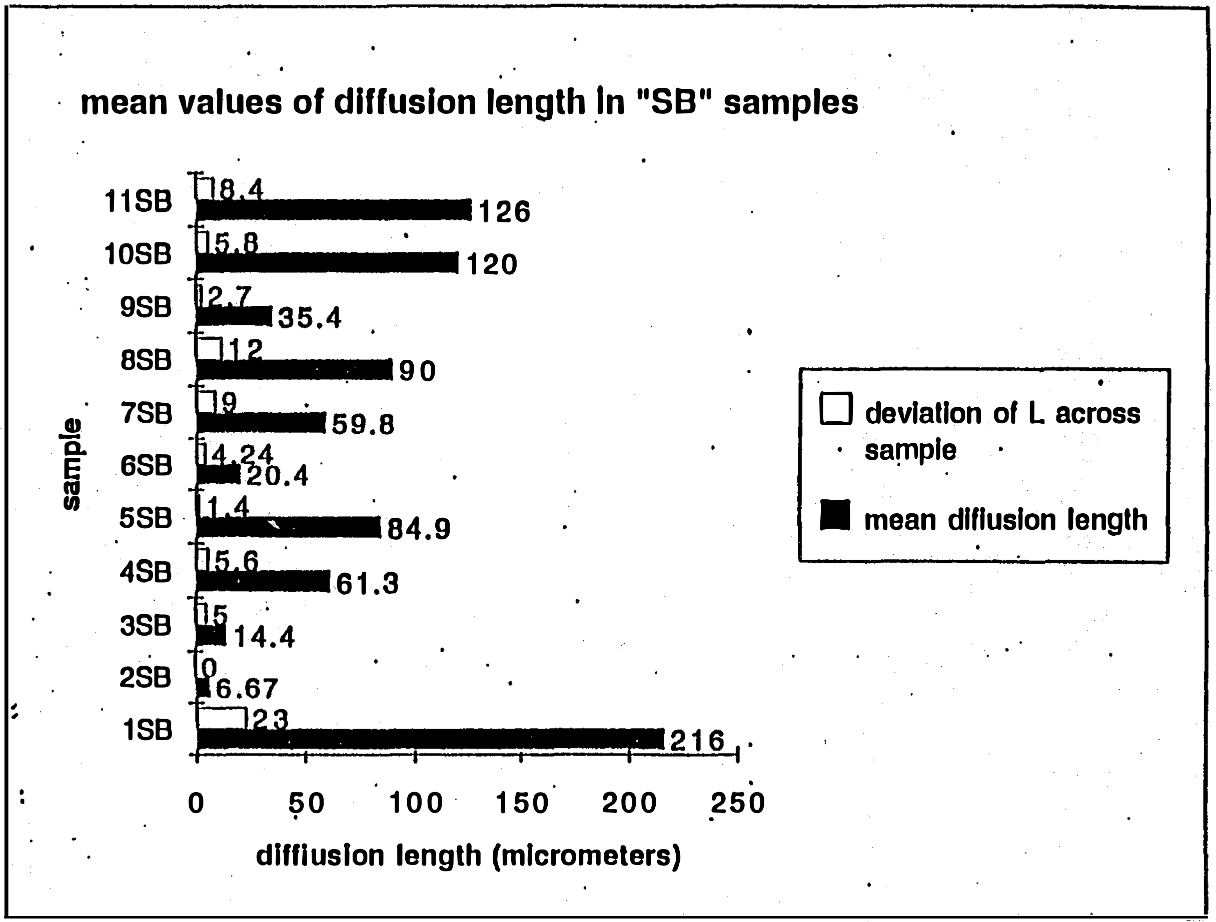
Table VI: Compilation of measurement results. All diffusion length values are in μm.

Raw Data from

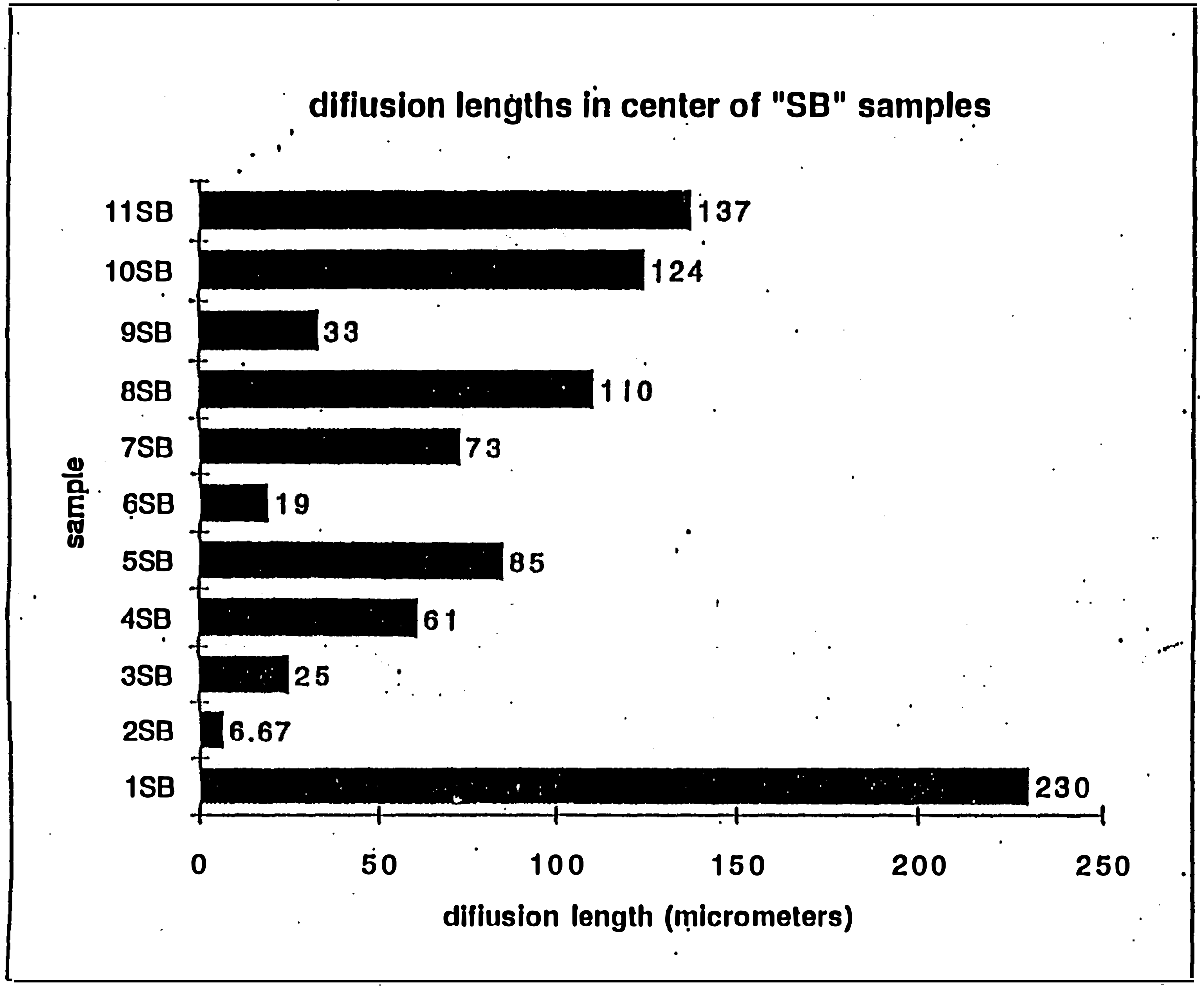
University of South Florida (USF)

Contact person: Dr. Lubek Jastrzebski

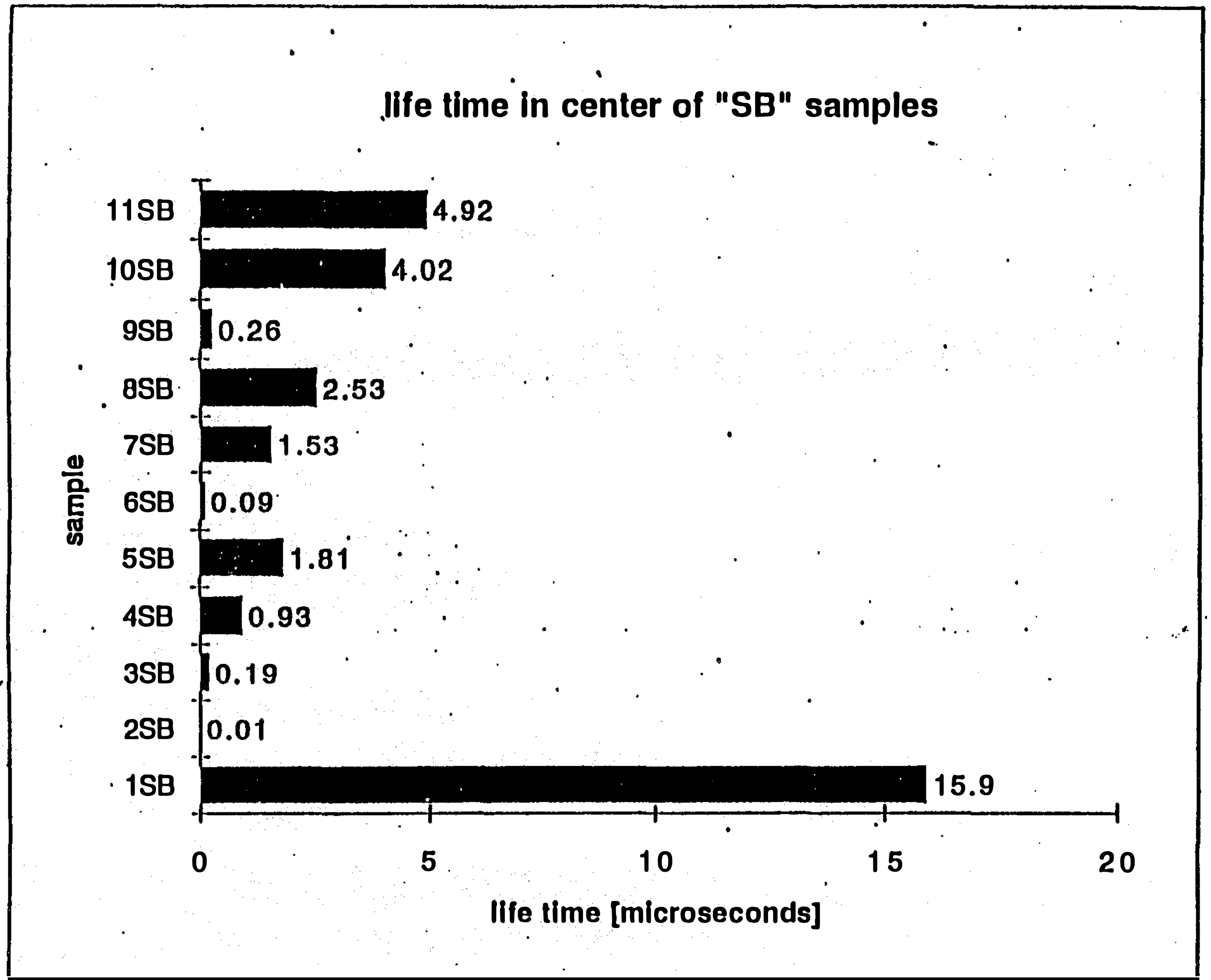
sbmp



mean values of diffusion length in "SB" samples
11SB
10SB
9SB
8SB
7SB
6SB
5SB
4SB
3SB
2SB
1SB
8.4
126
5.8
120
2.7
35.4
12
90
9
59.8
4.24
20.4
1.4
84.9
5.6
61.3
5
14.4
0
6.67
23
216
0
50
100
150
200
250
sample
diffiusion length (micrometers)
deviation of L across sample
mean diffusion length



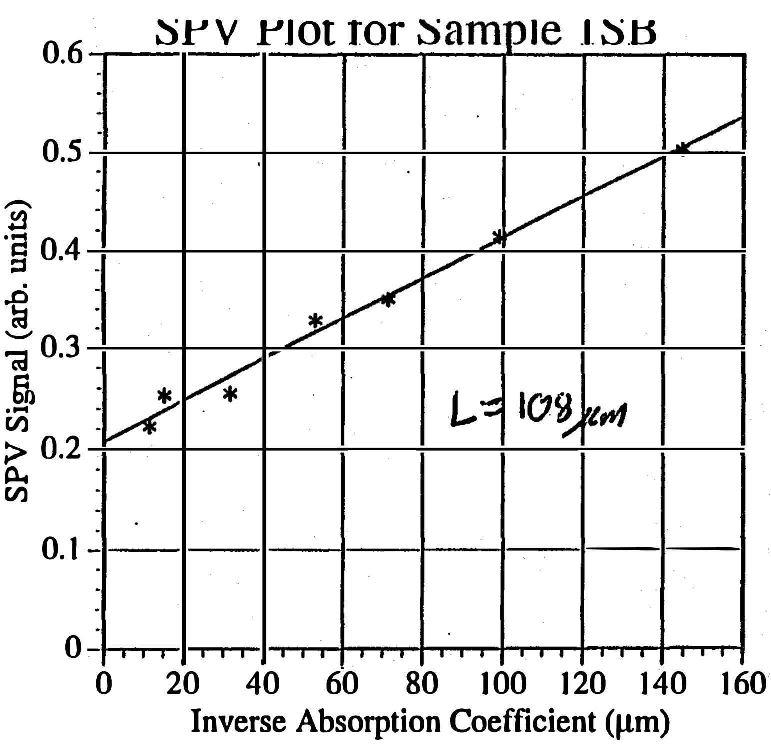
difiusion lengths in center of "SB" samples
sample
11SB
10SB
9SB
8SB
7SB
6SB
5SB
4SB
3SB
2SB
1SB
137
124
33
110
73
19
85
61
25
6.67
230
0
50
100
150
200
250
difiusion length (micrometers)

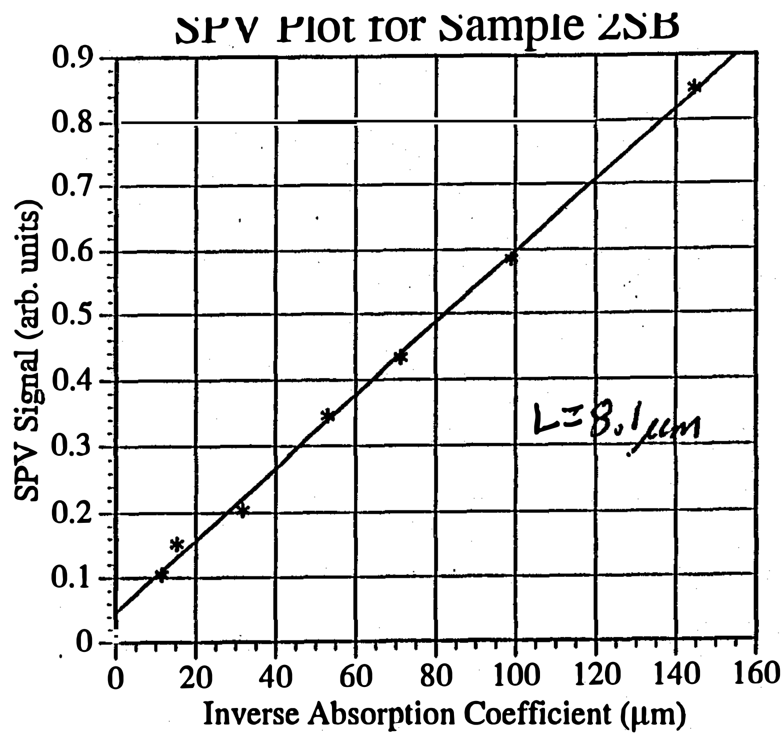

life time in center of "SB" samples
11SB
10SB
9SB
8SB
7SB
6SB
5SB
4SB
3SB
2SB
1SB
4.92
4.02
0.26
2.53
1.53
0.09
1.81
0.93
0.19
0.01
15.9
sample
0
5
10
15
20
life time [microseconds]

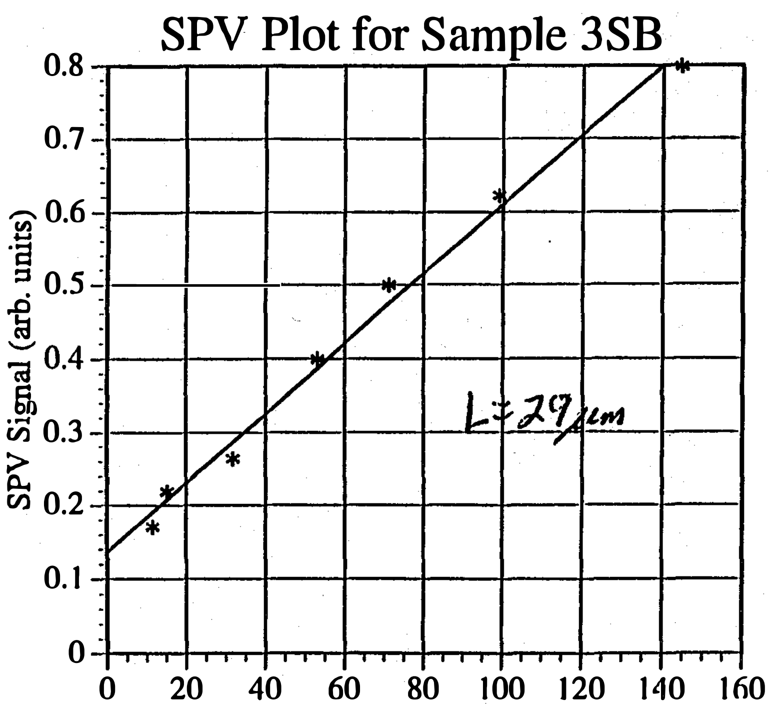
Raw Data from

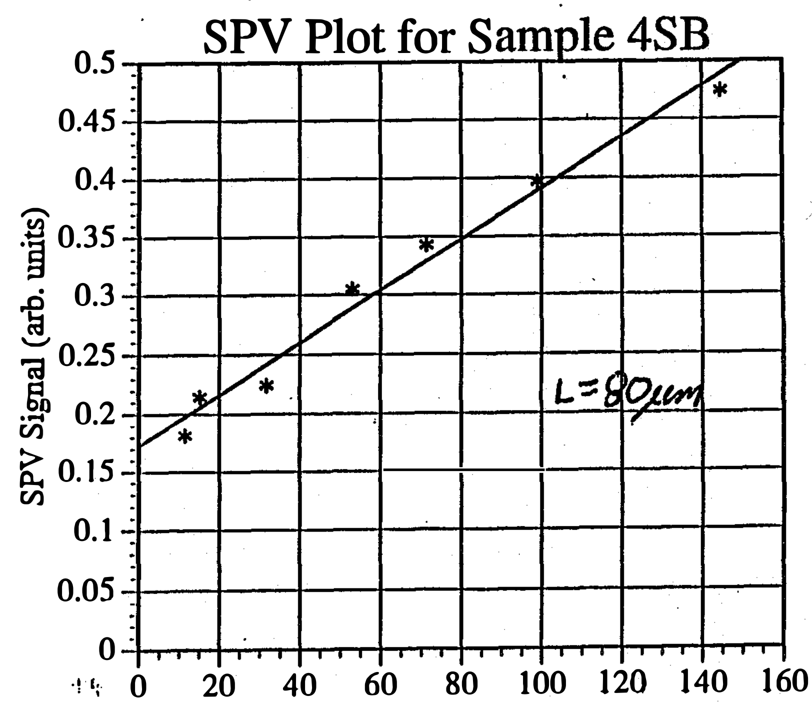
National Renewable Energy Laboratory (NREL)

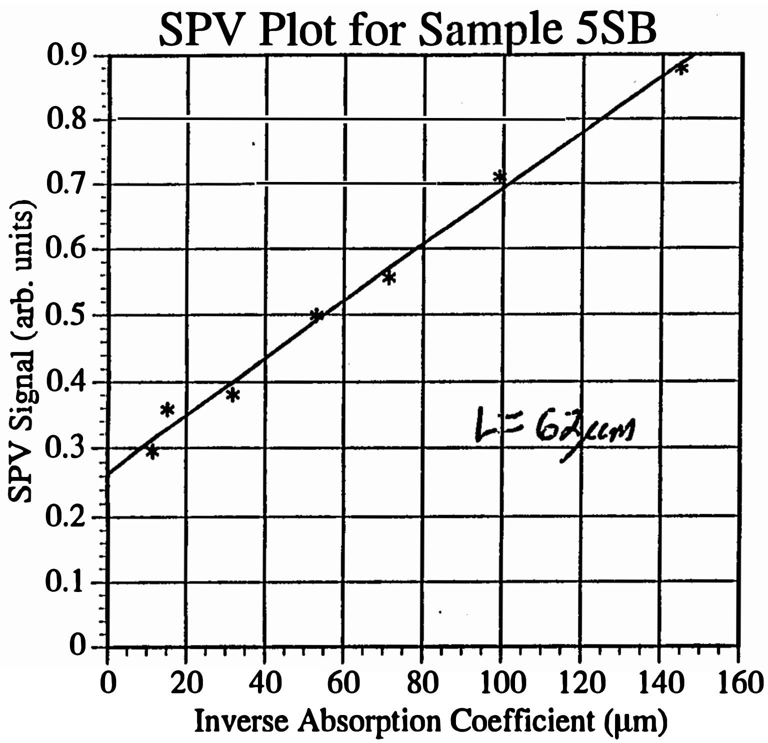
Contact person: Dr. Bhushan Sopori


SPV Plot for Sample 1SB
SPV Signal (arb. units)
0.6
0.5
0.4
0.3
0.2
0.1
0
0 20 40 60 80 100 120 140 160
Inverse Absorption Coefficient (µm)
L=108µm

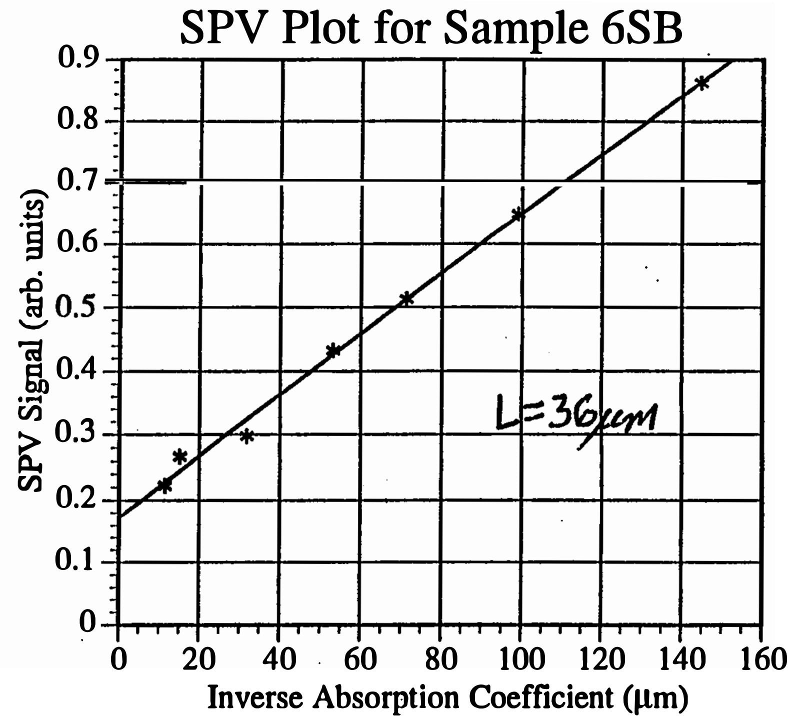

SPV Plot for Sample 2SB
SPV Signal (arb. units)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 20 40 60 80 100 120 140 160
Inverse Absorption Coefficient (µm)
L=8.1µm


SPV Plot for Sample 3SB
SPV Signal (arb. units)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 20 40 60 80 100 120 140 160
L=29µm

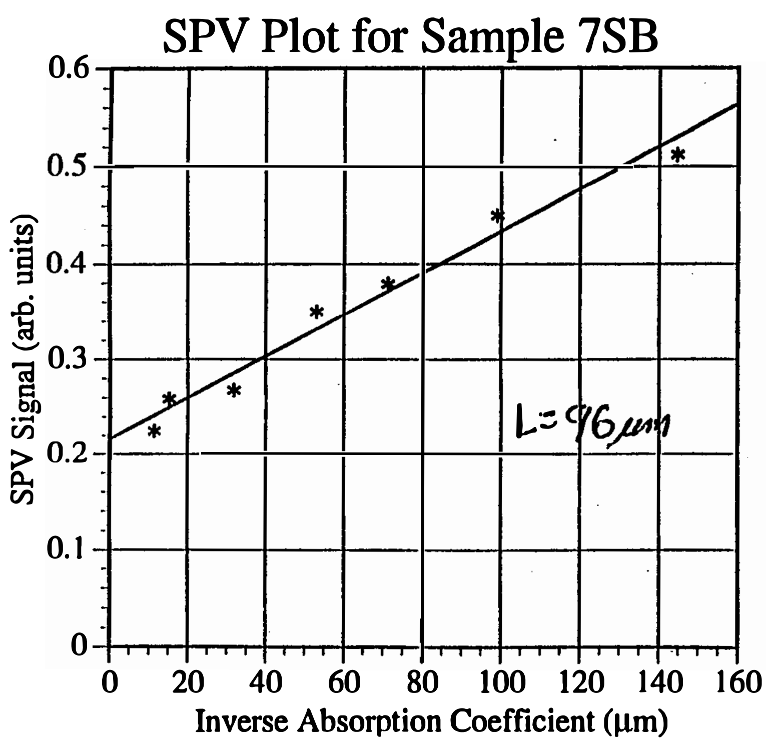

SPV Plot for Sample 4SB
SPV Signal (arb. units)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 20 40 60 80 100 120 140 160
L=80µm



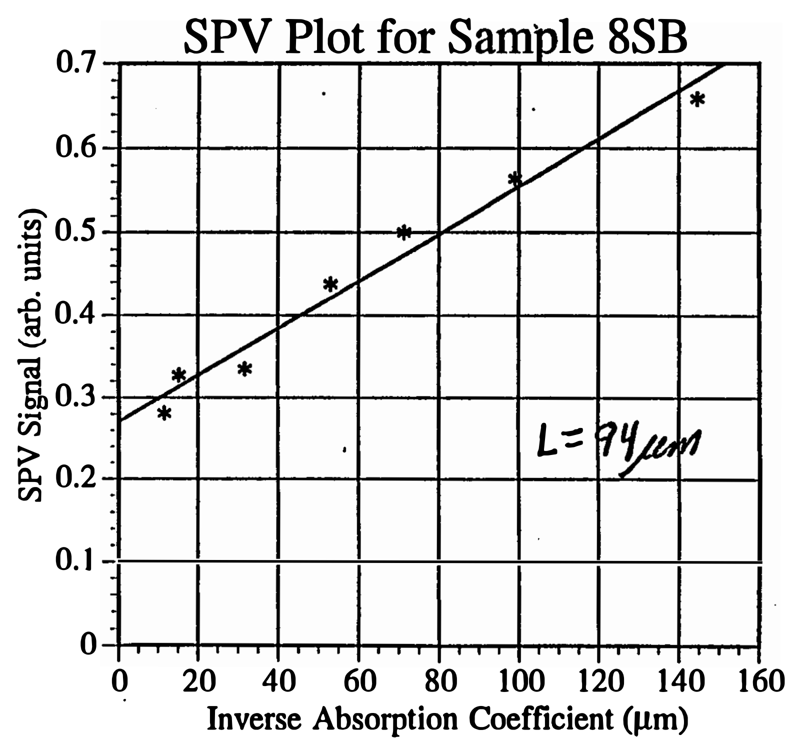
SPV Plot for Sample 5SB
SPV Signal (arb. units)
Inverse Absorption Coefficient (µm)
L=62µm



SPV Plot for Sample 6SB
SPV Signal (arb. units)
Inverse Absorption Coefficient (µm)
L=36µm

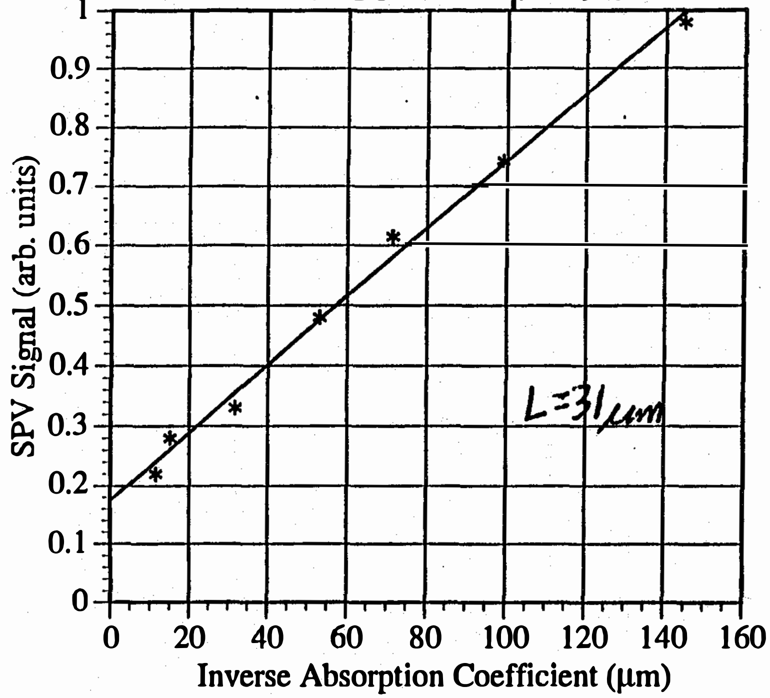


SPV Plot for Sample 7SB
SPV Signal (arb. units)
Inverse Absorption Coefficient (µm)
L=96µm

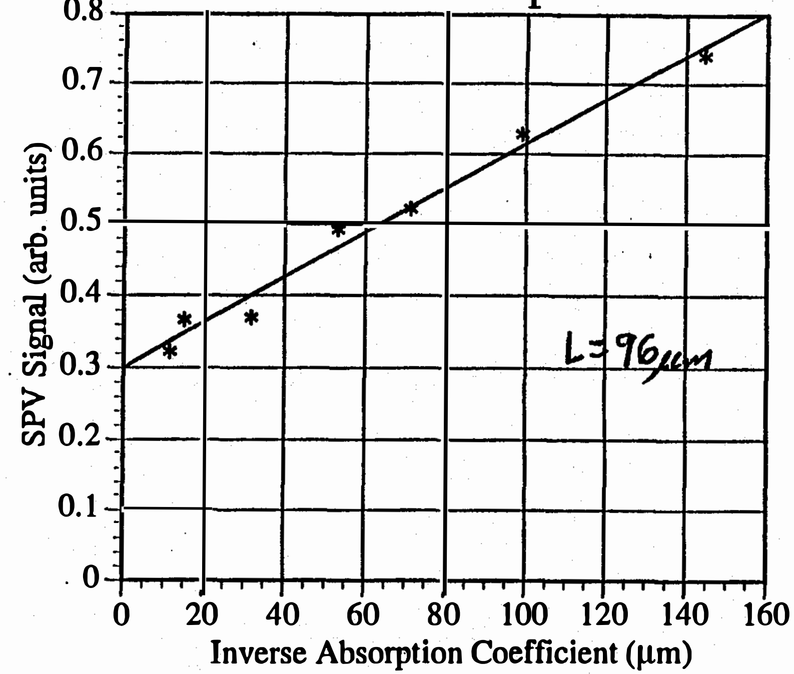


SPV Plot for Sample 8SB
SPV Signal (arb. units)
Inverse Absorption Coefficient (µm)
L=94µm

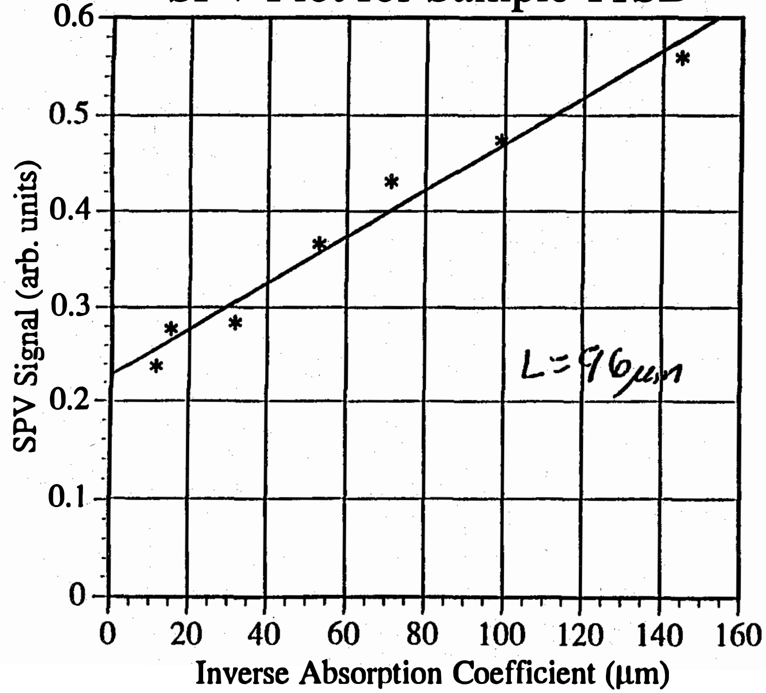
SPV Plot for Sample 9SB



SPV Plot for Sample 10SB



SPV Plot for Sample 11SB



Raw Data from

MEMC Electronics Materials, Inc.

Contact person: Dr. Kamal Mishra

SAMPLE #	Diffusion Length in Microns
1SB	248
2SB	6.8
3SB	28.6
4SB	80
5SB	96
6SB	21
7SB	77
8SB	100
9SB	41
10SB	134
11SB	144

Raw Data from

Mobil Solar

Contact person: Dr. Juris Kalejs

Mobil Solar Energy Corporation
4 Suburban Park Drive
Billerica, MA 01821

October 28, 1993

Dr. B. Sopori
NREL
1617 Cole Boulevard
Golden, CO 80401

Dear Bhushan:

I am returning the results of the measurements made with our PCD apparatus on the round-robin silicon samples. Enclosed also is a data sheet with the lifetime values. Two values and their relative amplitudes are given: τ_1 represents the short-time and τ_2 the long time component in the decay curve. I have also attached decay curves for the samples.

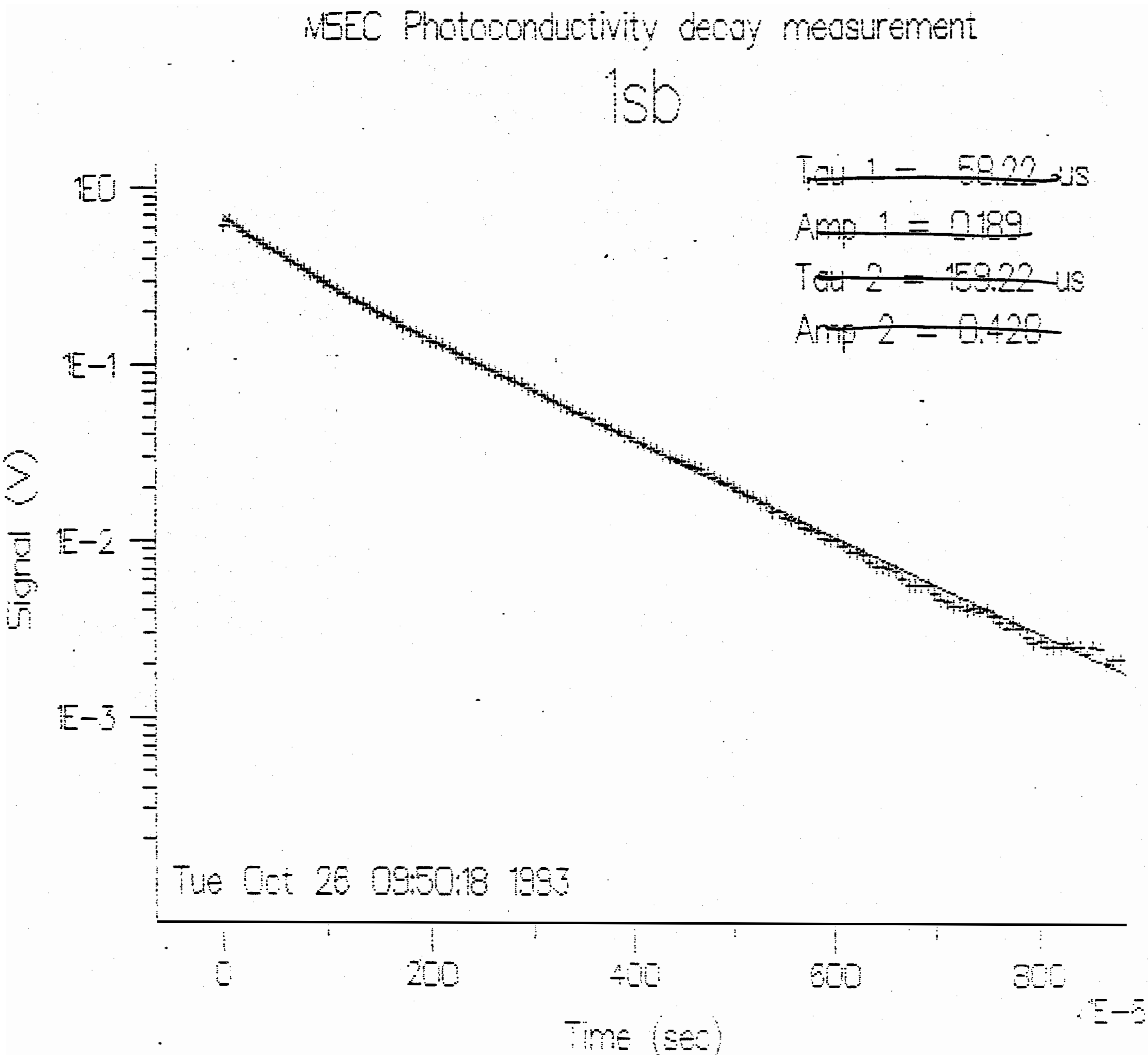
Let me know if you need additional clarification on the results.

Best Regards,

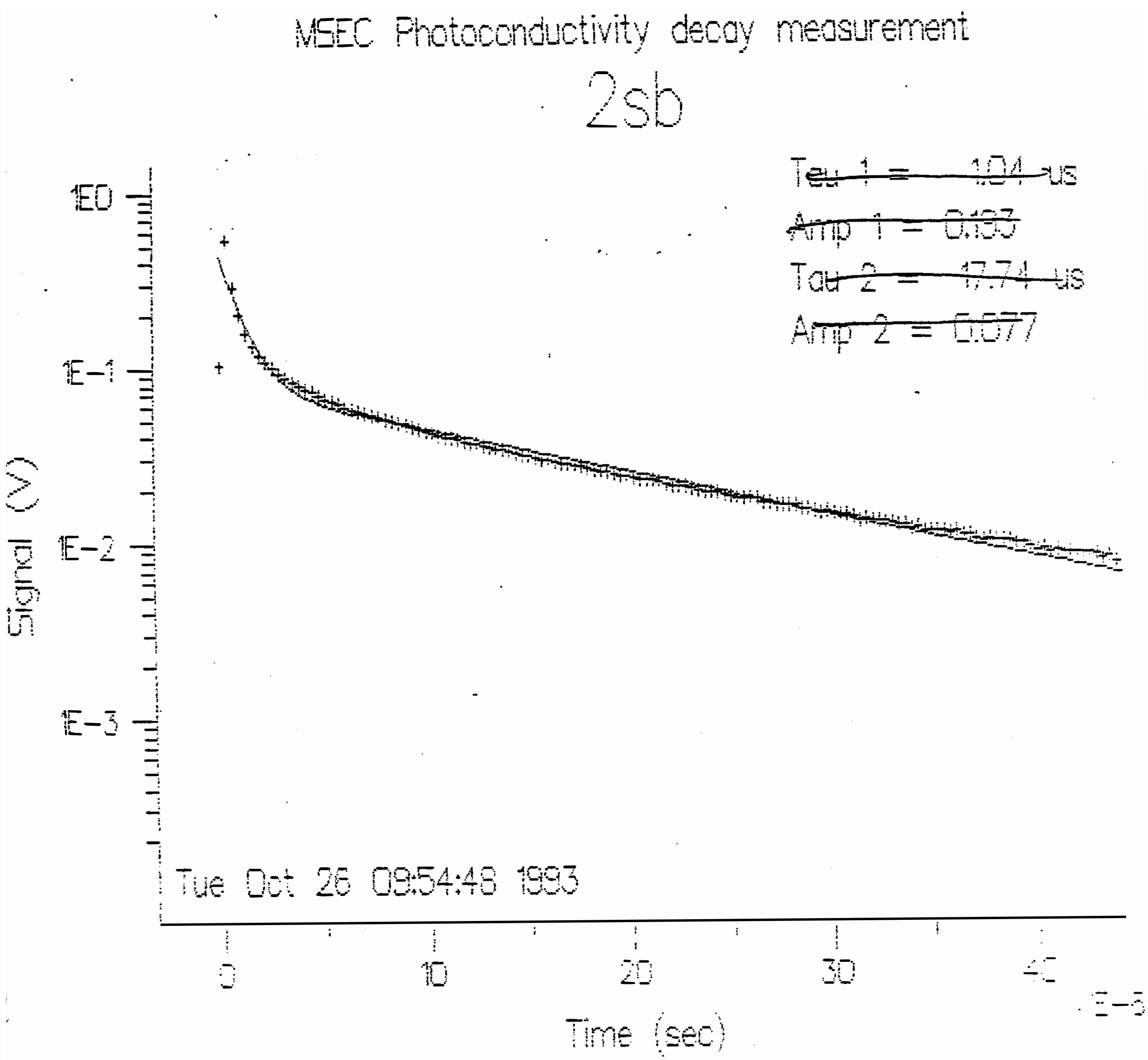
Juris Kalejs

Summary of PCD Measurements Made in HF at Mobil Solar
October 27, 1993

Sample	τ_1	A_1	τ_2	A_2	Comments
1	64	0.25	150	0.36	Double Component
2	1.2-43		17-500	-	Not a good exponential curve, Too Slow a Decay
3	0.75	0.17	6.1	0.08	Double Component
4	11	0.45	-	-	Single Component
5	17	0.5	-	-	Not a good exponential curve, Too Rapid a Decay
6	0.6	0.56	1.9	0.09	Double Component
7	11	0.6	-	-	Single component
8	17	0.5	-	-	Single component
9	1.0	0.29	2.9	0.23	Double Component
10	45	0.5	-	-	Double component
11	55-83	0.5	-	-	Not a good exponential curve, Too Rapid a Decay

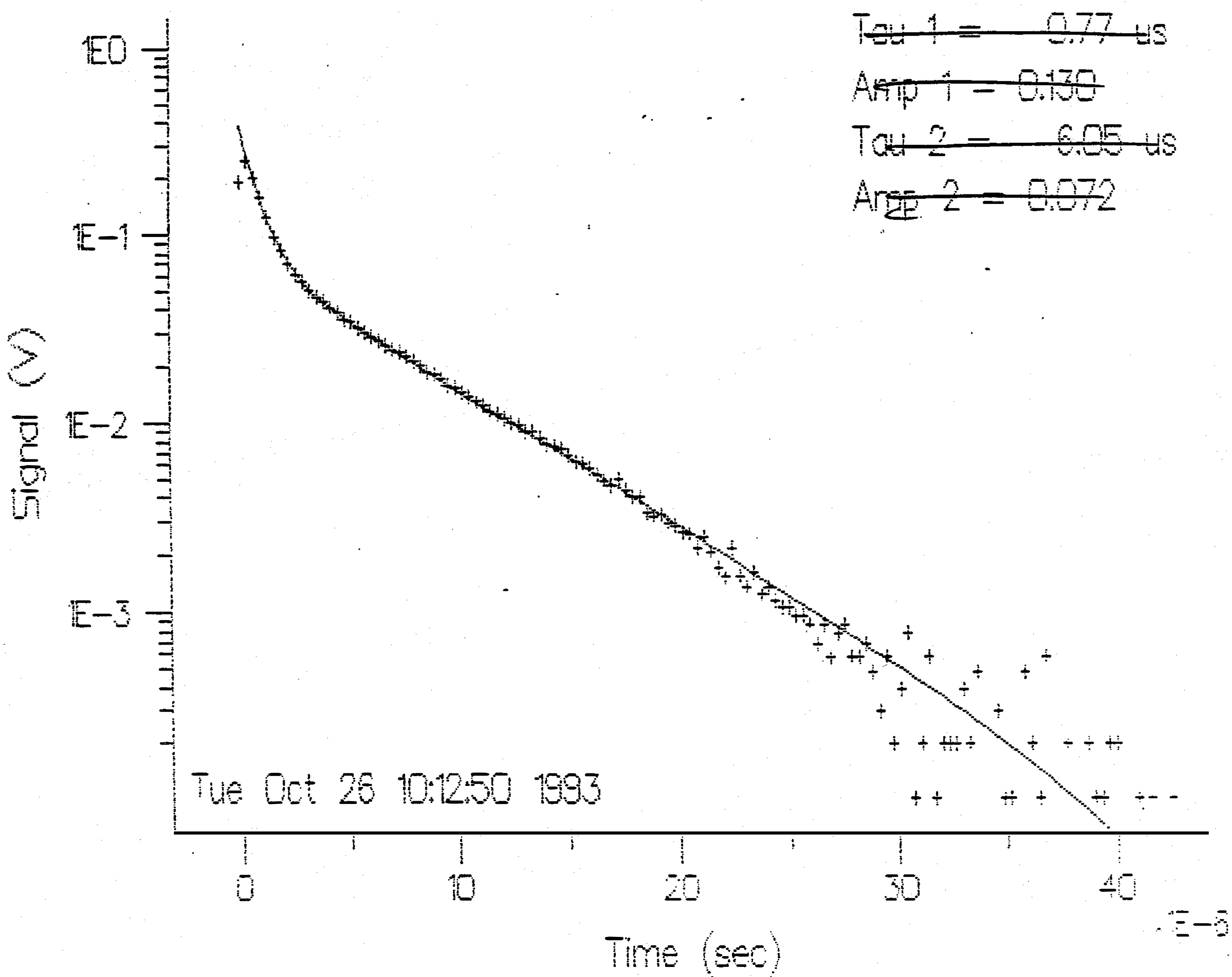


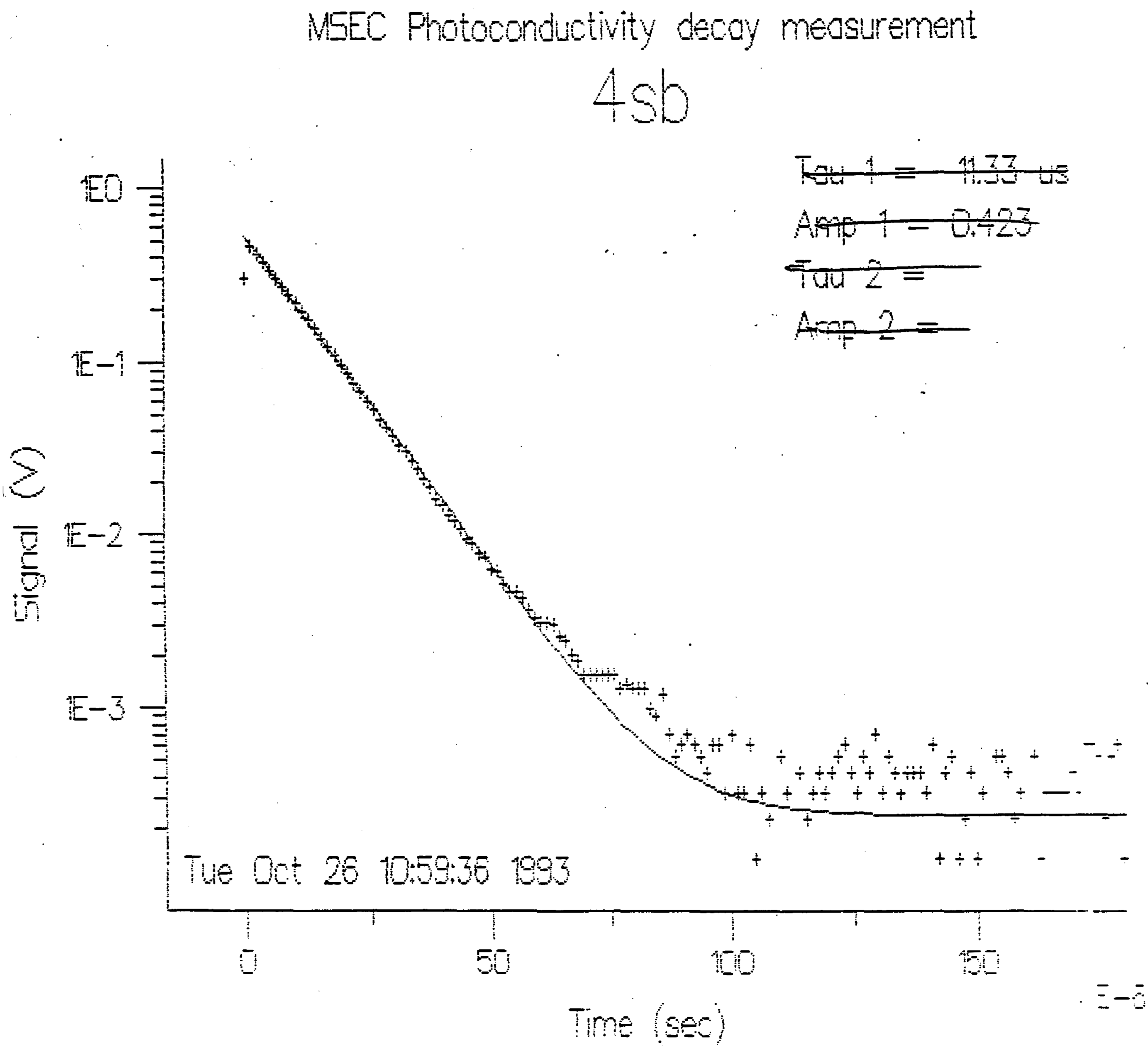
MSEC Photoconductivity decay measurement
1sb
Tau 1 = 58.22 us
Amp 1 = 0.189
Tau 2 = 159.22 us
Amp 2 = 0.428
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 09:50:18 1993
0
200
400
600
800
*E-6
Time (sec)


MSEC Photoconductivity decay measurement
2sb
Tau 1 = 1.04 us
Amp 1 = 0.133
Tau 2 = 17.74 us
Amp 2 = 0.077
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 09:54:48 1993
0
10
20
30
40
E-6
Time (sec)

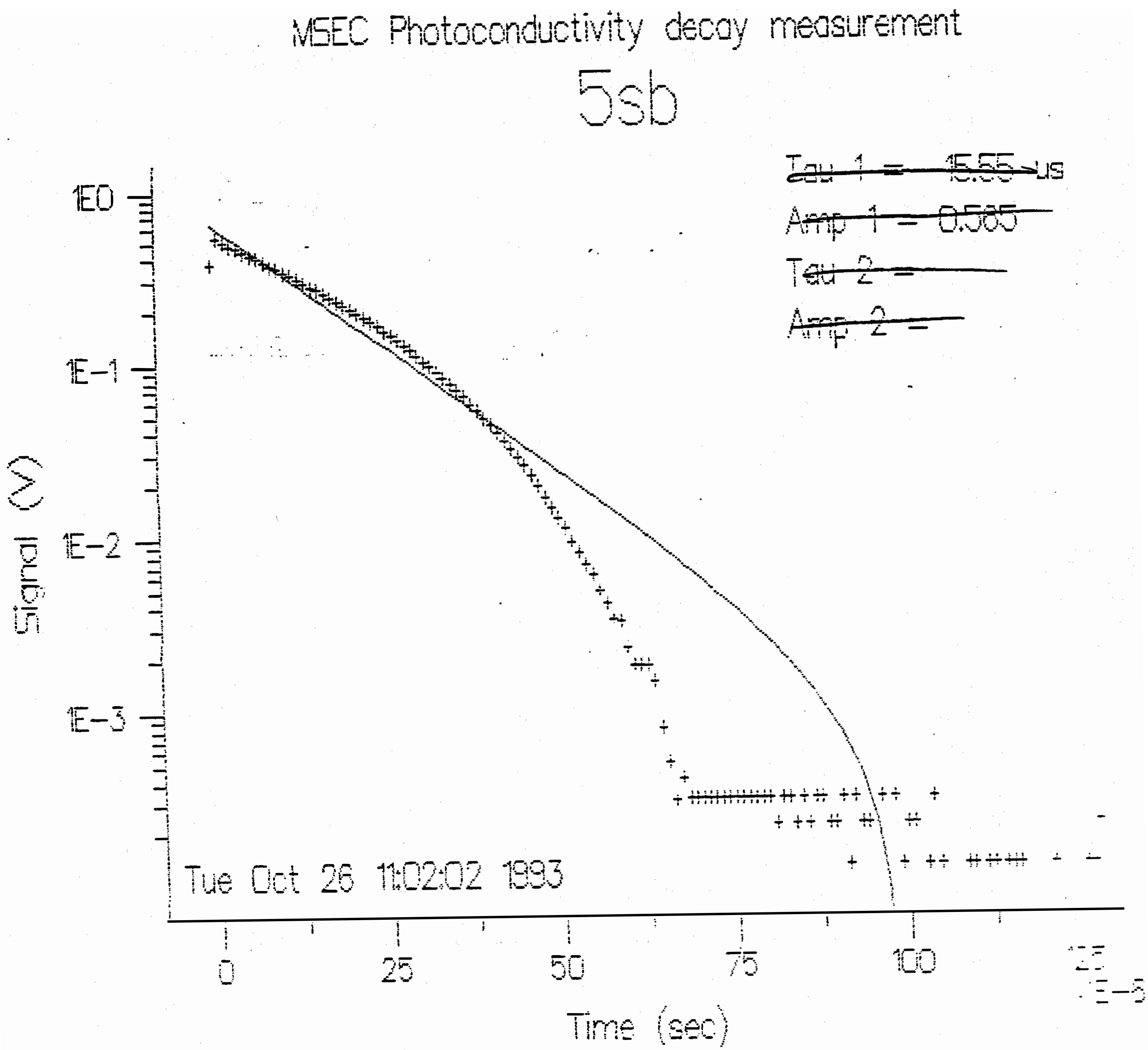
MSEC Photoconductivity decay measurement

3sb

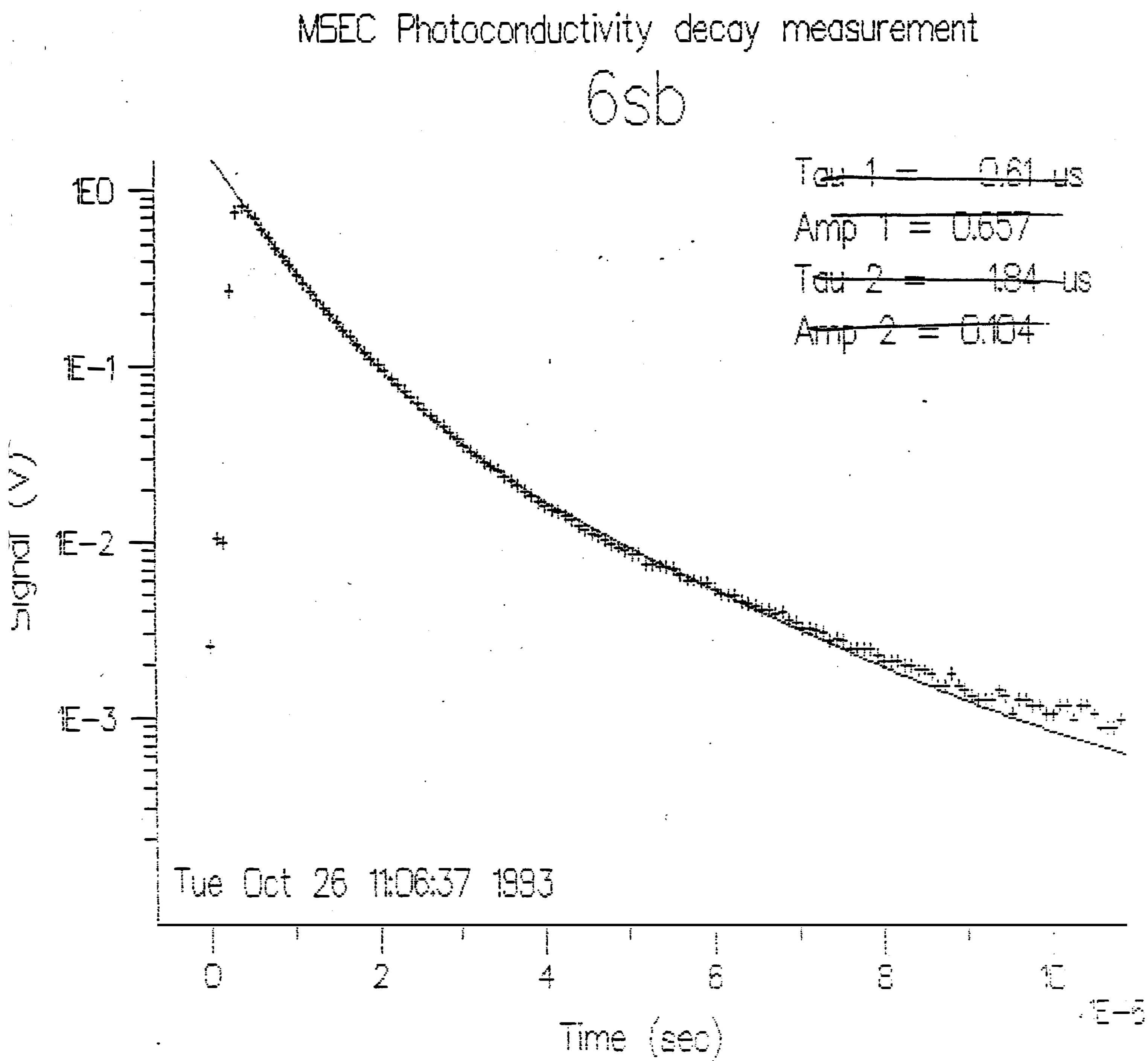




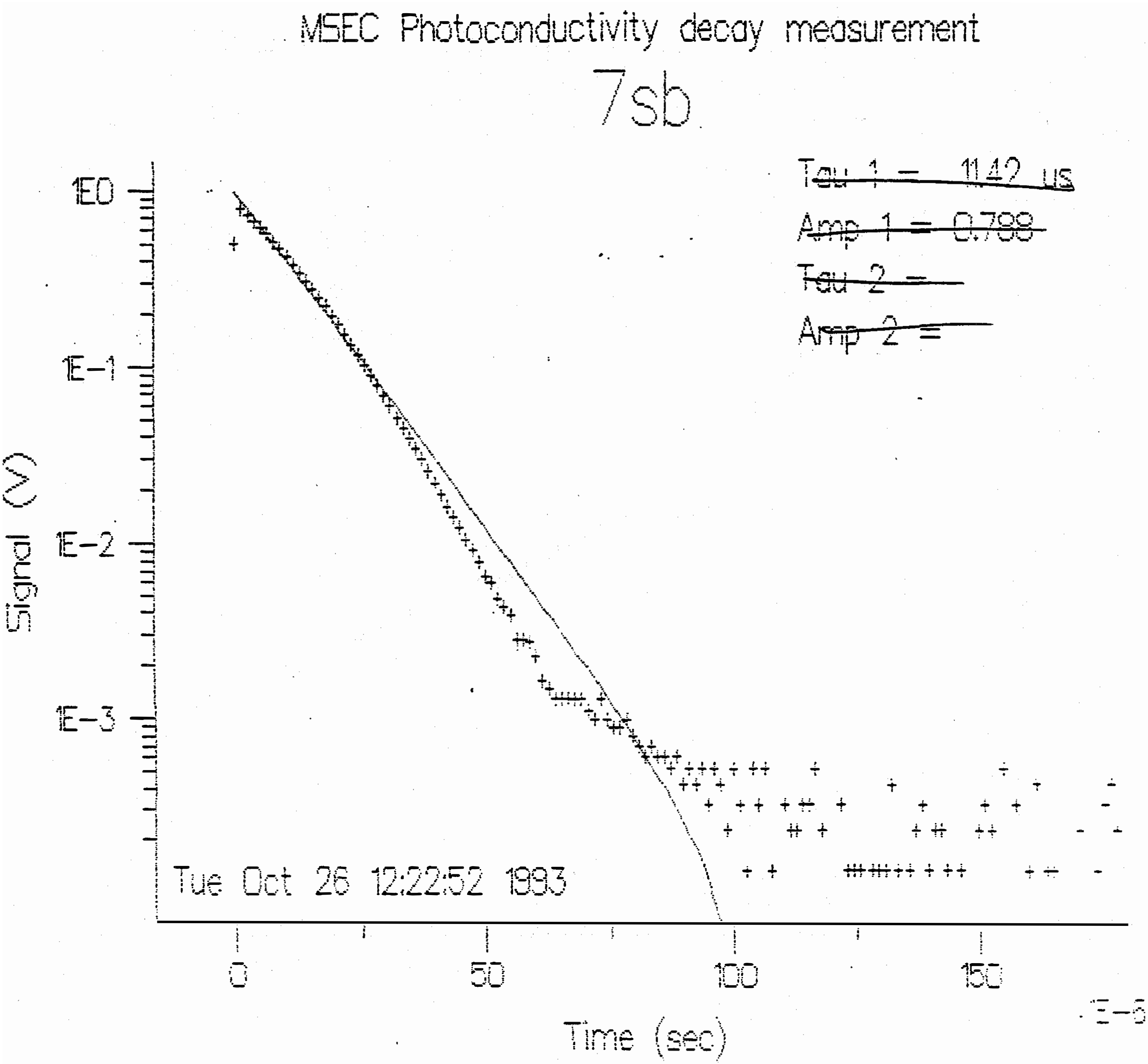
MSEC Photoconductivity decay measurement
4sb
Tau 1 = 11.33 us
Amp 1 = 0.423
Tau 2 =
Amp 2 =
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 10:59:36 1993
0
50
100
150
E-6
Time (sec)



MSEC Photoconductivity decay measurement
5sb
Tau 1 = 15.55 us
Amp 1 = 0.585
Tau 2 =
Amp 2 =
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 11:02:02 1993
0
25
50
75
100
E-6
Time (sec)



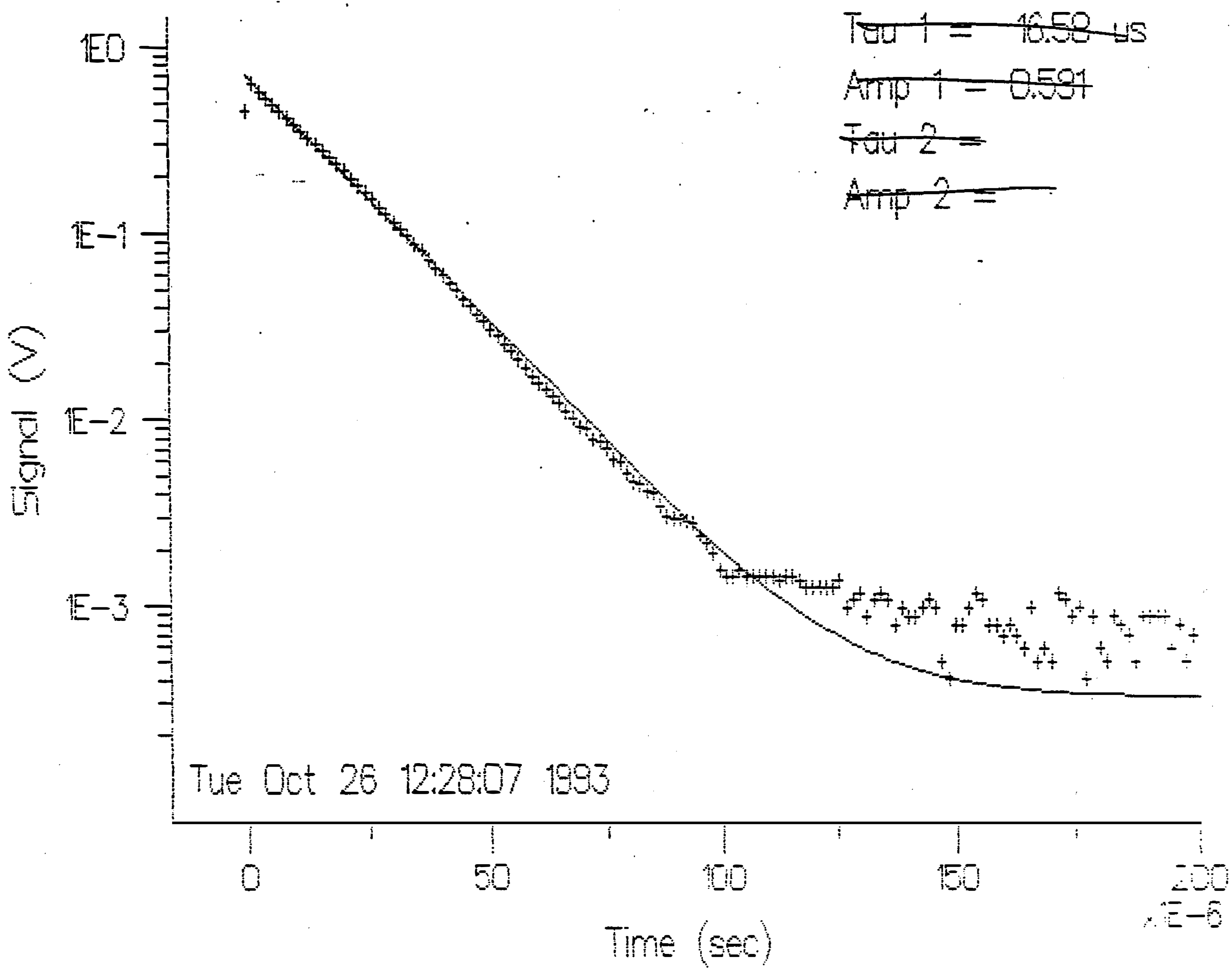
MSEC Photoconductivity decay measurement
6sb
Tau 1 = 0.61 us
Amp 1 = 0.657
Tau 2 = 1.84 us
Amp 2 = 0.104
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 11:06:37 1993
0
2
4
6
8
10
1E-6
Time (sec)



MSEC Photoconductivity decay measurement
7sb
Tau 1 = 11.42 us
Amp 1 = 0.788
Tau 2 =
Amp 2 =
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 12:22:52 1993
0
50
100
150
E-6
Time (sec)

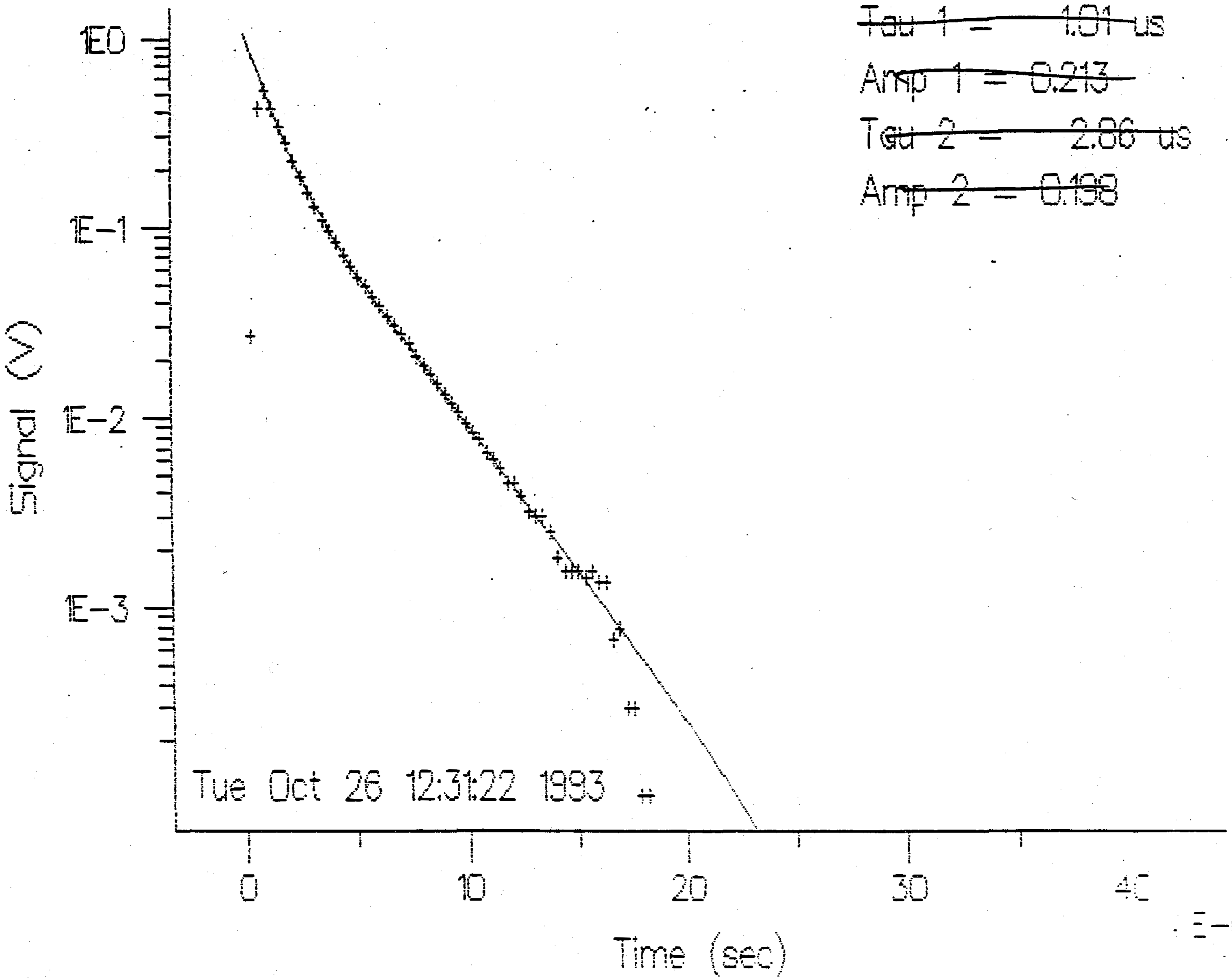
MSEC Photoconductivity decay measurement

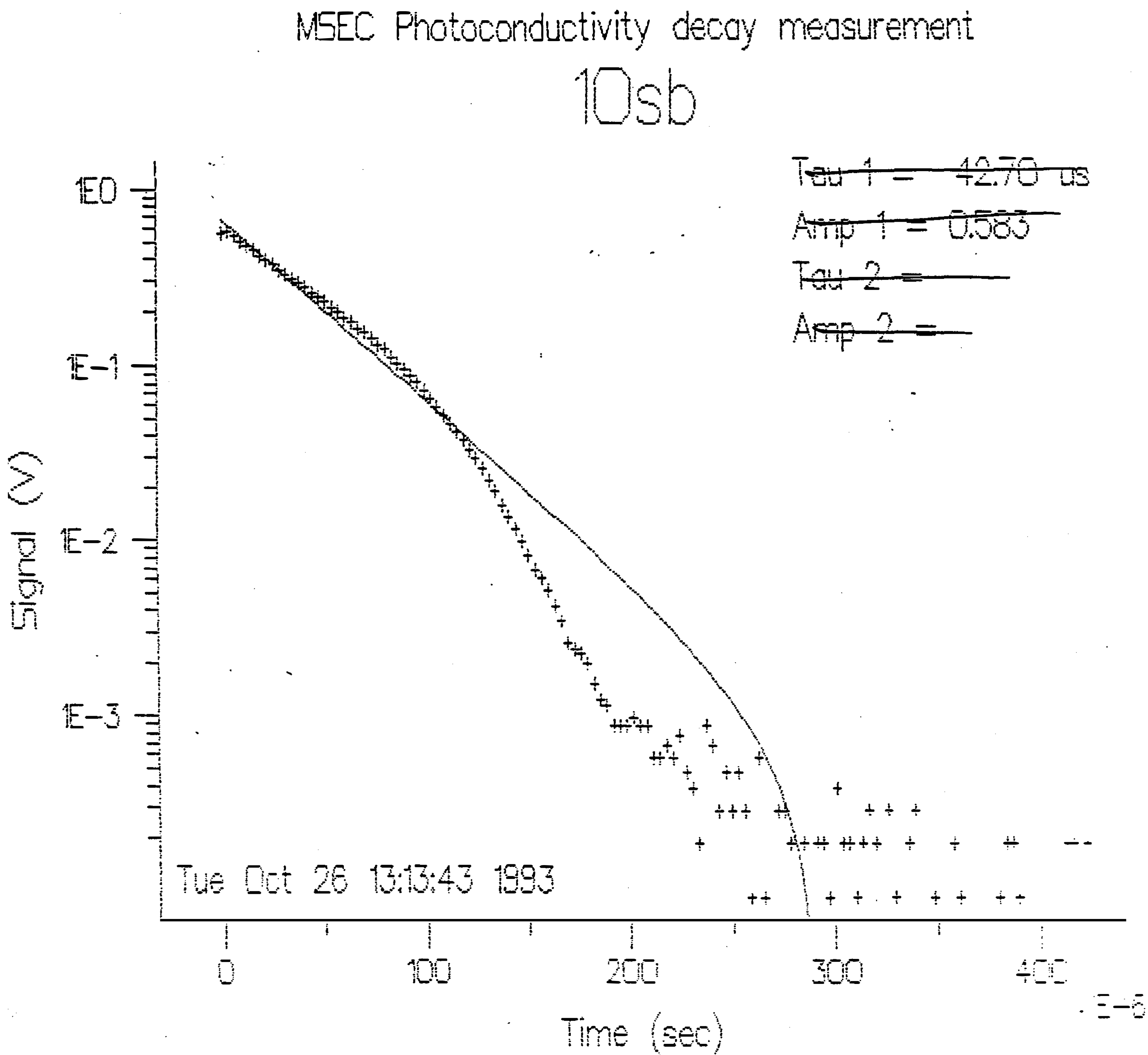
8sb

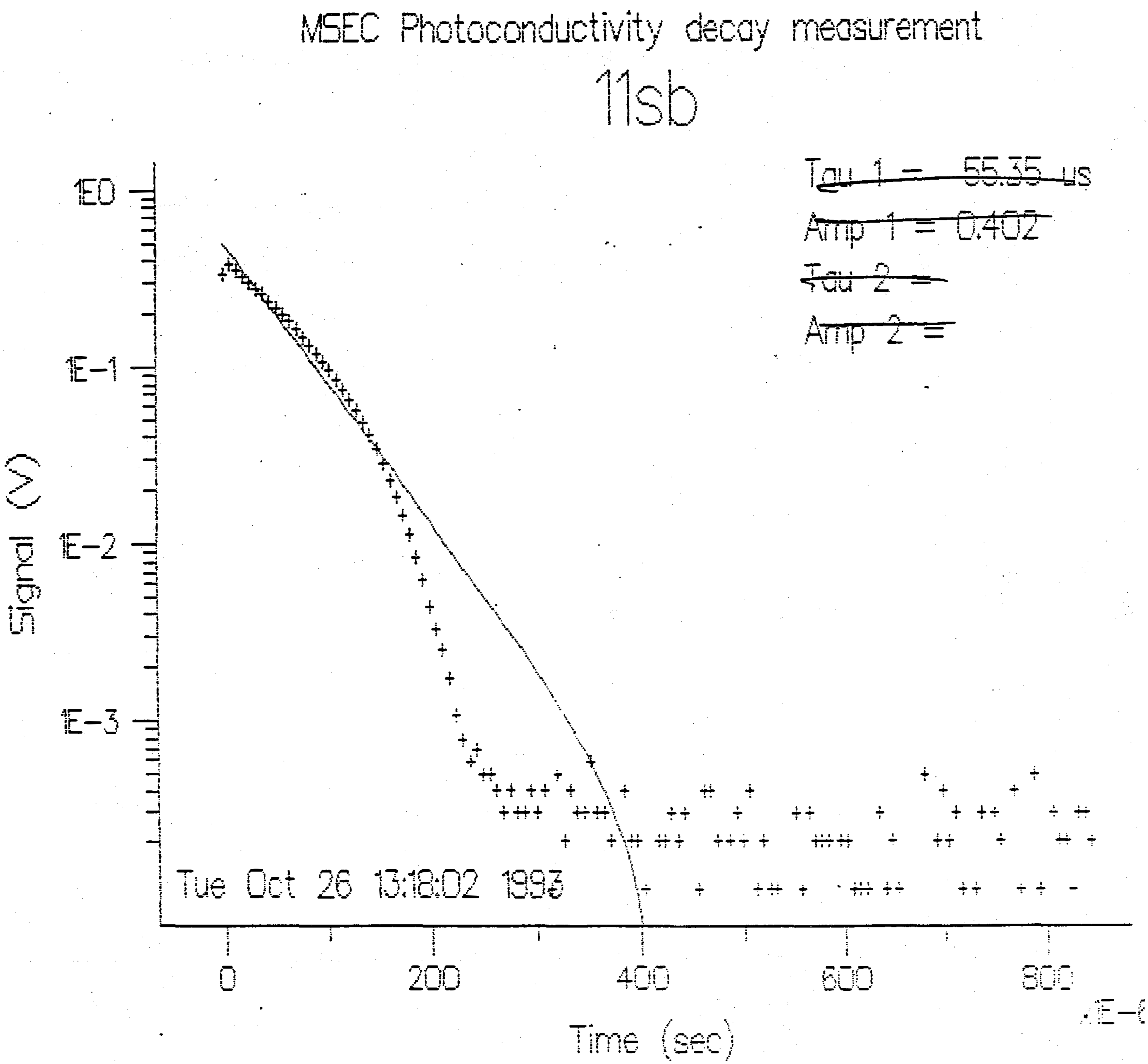


MSEC Photoconductivity decay measurement

9sb




MSEC Photoconductivity decay measurement
10sb
Tau 1 = 42.70 us
Amp 1 = 0.583
Tau 2 =
Amp 2 =
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 13:13:43 1993
0
100
200
300
400
E-6
Time (sec)



MSEC Photoconductivity decay measurement
11sb
Tau 1 = 55.35 us
Amp 1 = 0.402
Tau 2 =
Amp 2 =
1E0
1E-1
1E-2
1E-3
Signal (V)
Tue Oct 26 13:18:02 1993
0
200
400
600
800
Time (sec)

Raw Data from

Massachusettes Institute of Technology (MIT)

Contact person: Dr. Lionel Kimerling

NREL τ/L Round-Robin Analysis : RFPCD Results

Sample ID	Lifetime (μs)
1SB	33.0
2SB	50.4
3SB	<1
4SB	20.3
5SB	<1
6SB	<1
7SB	15.4
8SB	25.8
9SB	2.7
10SB	20.3
11SB	16.9

Gerd Norga (MIT) 6/20/94

Raw Data from

North Carolina State Univeristy (NCSU)

Contact person: Dr. George Rozgonyi

Lifetime Measurements
On Samples Received for Round Robin Analysis

Performed by: North Carolina State University (Prof.G.A.Rozgonyi Group)
Measurement Technique: LM-PCD (Lifetech-88® from SEMITEX Co., Ltd)

A set of eleven samples described in Table I was received for lifetime measurements. No specific information about the sample preparation was supplied. The samples were measured with the transient laser/ microwave photoconductance decay (LM-PC) technique using Lifetech-88® system (SEMITEX Co., Japan). Low injection level was satisfied during wafer excitation and a laser wavelength 854 nm was used except for wafer #1, where a laser wavelength of 904 nm was applied. The sample resistivity was obtained using a standard four point probe.

Table I. Wafer specification

number	original name	renamed as
#1	1SB	nrel-1
#2	2SB	nrel-2
#3	3SB	nrel-3
#4	4SB	nrel-4
#5	5SB	nrel-5
#6	6SB	nrel-6
#7	7SB	nrel-7
#8	8SB	nrel-8
#9	9SB	nrel-9
#10	10SB	nrel-10
#11	11SB	nrel-11

Based on the wafer conductivity type and resistivity, an electron mobility equal to 400 cm^2/Vs was assumed for calculations of τ_{surf}. Assuming this value of electron mobility and the average thickness of the sample about 300 μm the "raw" calculations show, that the lowest possible τ_{surf} in such a samples is on the order of 10 μs. Since the measured τ_{eff} is much shorter than 10 μs, this implies that essentially $\tau_{eff} = \tau_{bulk}$, i.e. the bulk recombination process is dominant.

Z. Helak, *North Carolina State University*, 02/10/94

SUMMARY OF RESULTS

Table II. Lifetime measurement results

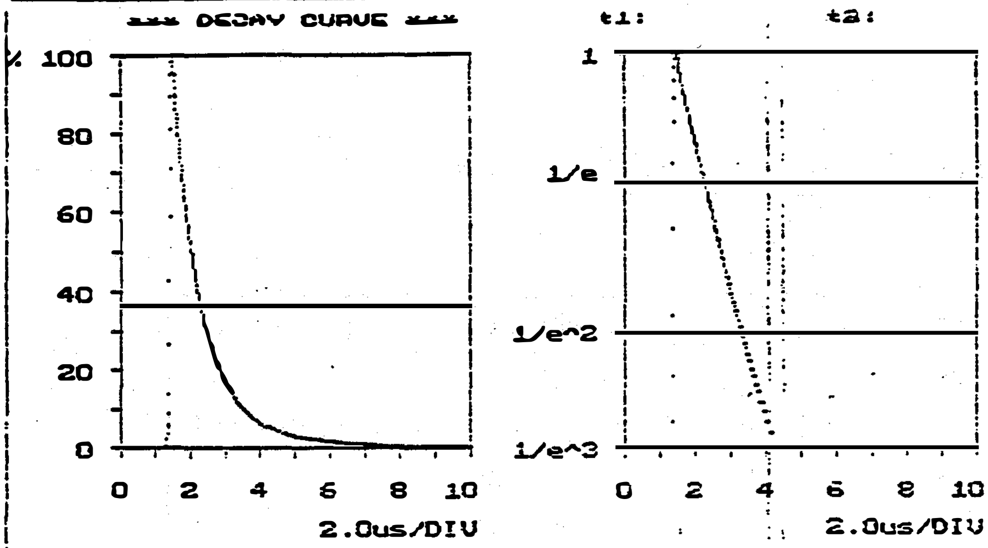
Sample	lifetime (τ_{eff})	lifetime (τ_{surf})	lifetime (τ_{bulk})	Comments
1SB	1.64 µs	*	1.6 µs	
2SB	-	-	-	too low signal
3SB	1.57 µs	*	1.57 µs	
4SB	1.25 µs	*	1.25 µs	
5SB	2.08 µs	*	2.08 µs	
6SB	< 0.3 µs	*	-	laser peak
7SB	1.87 µs	*	1.87 µs	
8SB	0.85 µs	*	0.85 µs	
9SB	1.63 µs	*	1.63 µs	
10SB	< 0.3 µs	*	-	too low τ_{eff}
11SB	1.82 µs	*	1.82 µs	

'*' means, that the surface coefficient plays no role in recombination process and cannot be evaluated

'-' means, that no data was obtained because of very low signal

Table III. Wafer thickness and resistivity measurement results

Sample	current	voltage	thickness	resistivity
1SB	0.1 µA	350 mV	745 µm	> 100
2SB	1 mA	4.5 mV	894 µm	1,76
3SB	-	-	269 µm	-
4SB	10 mA	47.1 mV	440 µm	0.9
5SB	10 mA	85.3 mV	384 µm	1.43
6SB	1 mA	10 mV	375 µm	1.64
7SB	1 mA	10.5 mV	244 µm	1.12
8SB	10 mA	50 mV	455 µm	0.9
9SB	1 mA	17.5 mV	360 µm	2.75
10SB	1 mA	1.3 mV	383 µm	0.218
11SB	1 mA	18.6 mV	394 µm	3.2



DATE 1994/02/04

TIME 17:52:01

INPUT RANGE 20 mv

Wafer No: nrel-1

LASER POW L2 (65h)

LASER SEL LD1

INT. TIME 20ns

SAMPL P. 1024

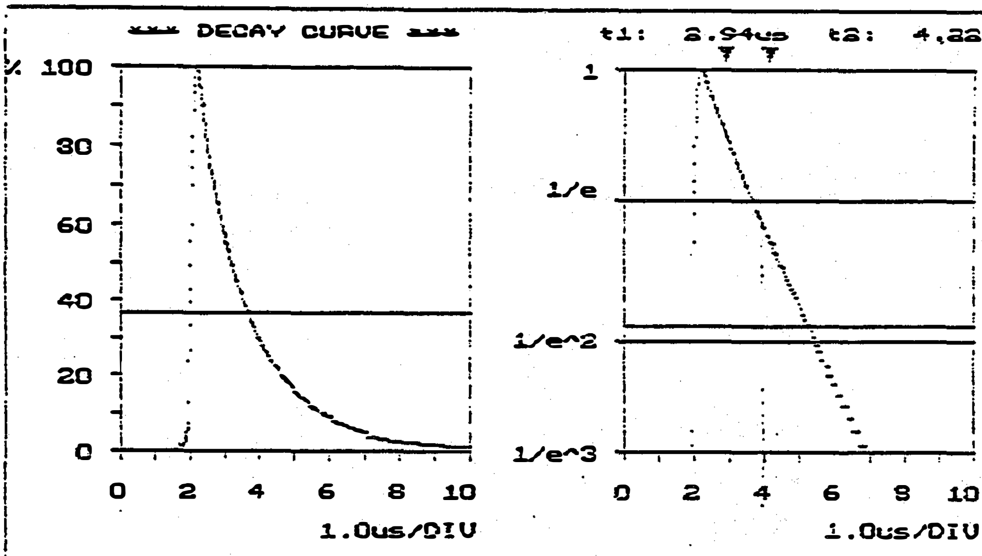
AVG. 256

DELAY 0.00ns

TEMP 27 °C

	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	16	1.64 us	
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END



DATE 1994/02/04

TIME 18:03:46

INPUT RANGE 20 mv

Wafer No: nrel-3

LASER POW L5 (99h)

LASER SEL LD2

INT. TIME 10ns

SAMPL P. 1024

AVG. 256

DELAY 0.00ns

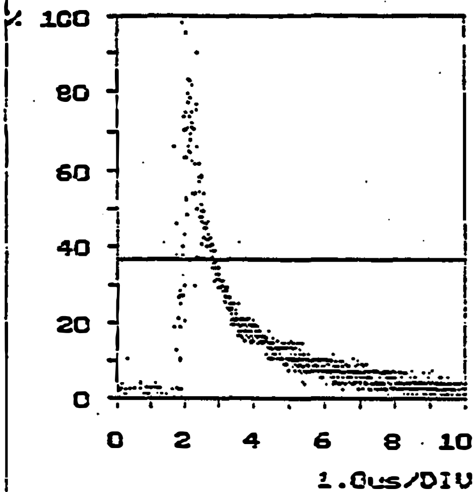
TEMP 27 °C

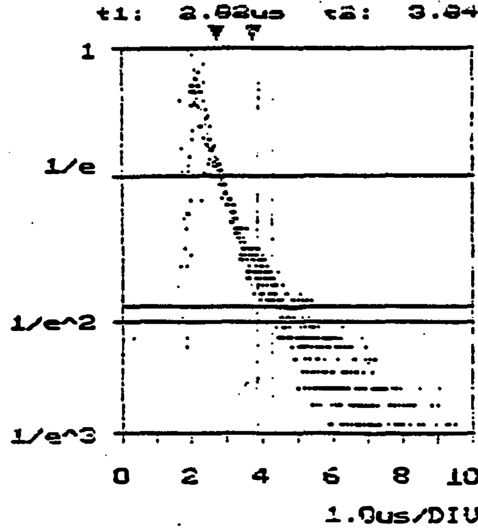
	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	12	1.49 us	1.57 us
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END

*** DECAY CURVE ***

t1: 2.82us t2: 3.84us





DATE 1994/02/04

TIME 18:14:43

INPUT RANGE 20 mv

Wafer No: nrel-4

LASER POW L5 (99h)

LASER SEL LD2

INT. TIME 10ns

SAMPL P. 1024

AVG. 256

DELAY 0.00ns

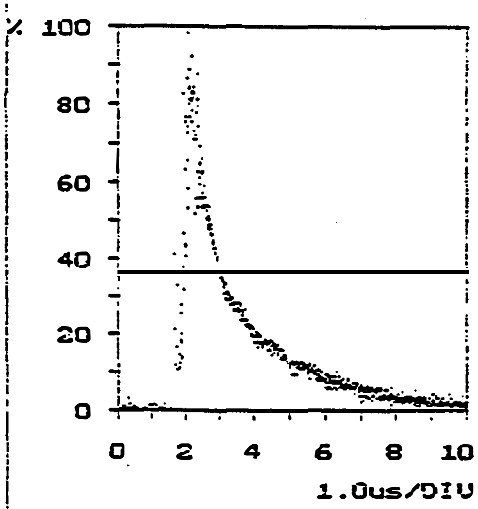
TEMP 27 °C

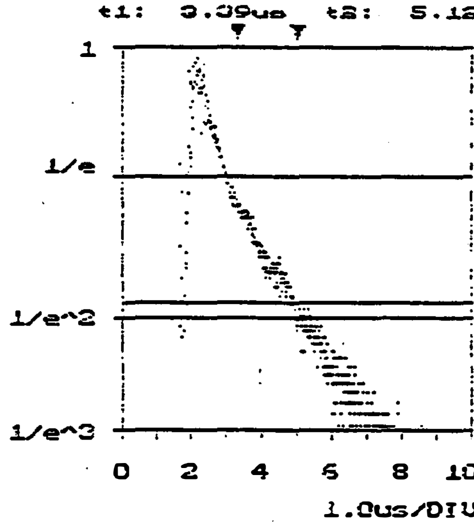
	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	9	10.00 ns	1.25 us
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END

*** DECAY CURVE ***

t1: 3.39us t2: 5.12us





DATE 1994/02/04

TIME 18:24:24

INPUT RANGE 20 mv

Wafer no: nrel-5

LASER POW L5 (99h)

LASER SEL LD2

INT. TIME 10ns

SAMPL P. 1024

AVG. 256

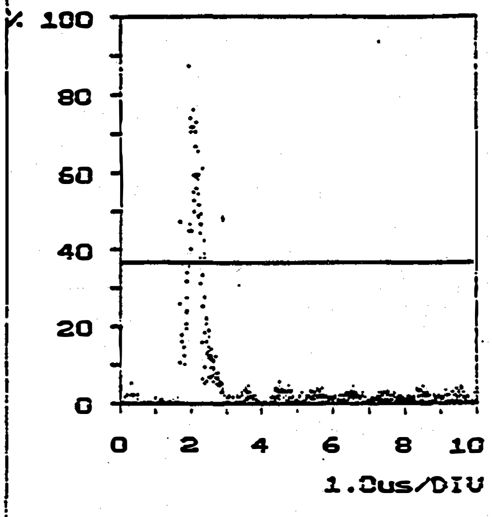
DELAY 0.00ns

TEMP 27 °C

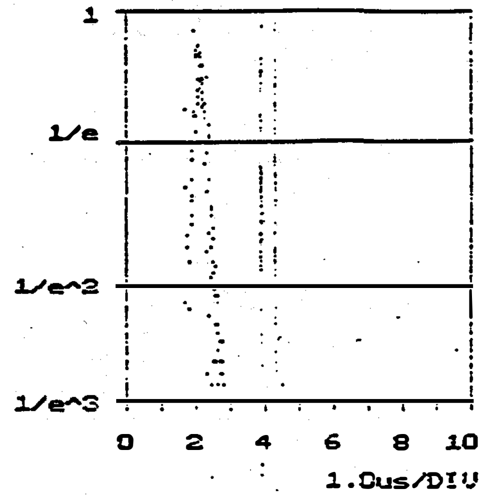
	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	15	660.00 ns	2.08 us
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END

*** DECAY CURVE ***



t1: t2:



	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	14	220.00 ns	
2					
3					
4					
5					

DATE 1994/02/04

TIME 18:29:15

INPUT RANGE 20 mv

Wafer no: nrel-6

LASER POW L5 (99h)

LASER SEL LD2

INT. TIME 10ns

SAMPL P. 1024

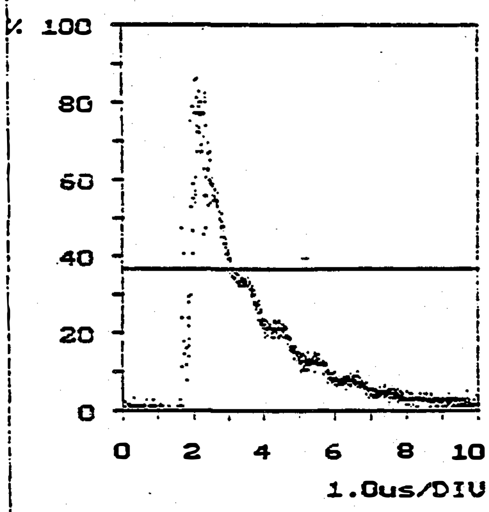
AVG. 256

DELAY 0.00ns

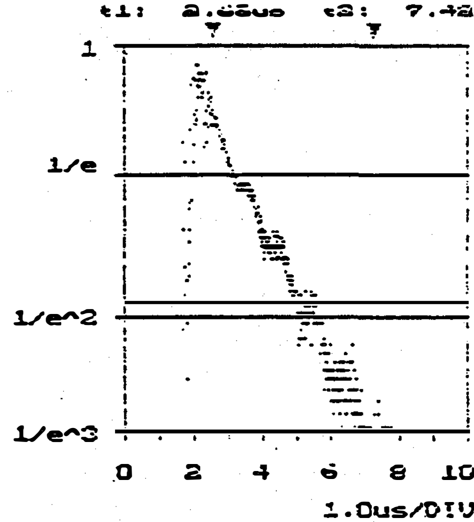
TEMP 27 °C

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END

*** DECAY CURVE ***



t1: 2.66us t2: 7.42us



	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	LIFETIME log
1	+00.0	+00.0	14	1.06 us	1.87 us
2					
3					
4					
5					

DATE 1994/02/04

TIME 18:38:09

INPUT RANGE 20 mv

Wafer no: nrel-7

LASER POW L5 (99h)

LASER SEL LD2

INT. TIME 10ns

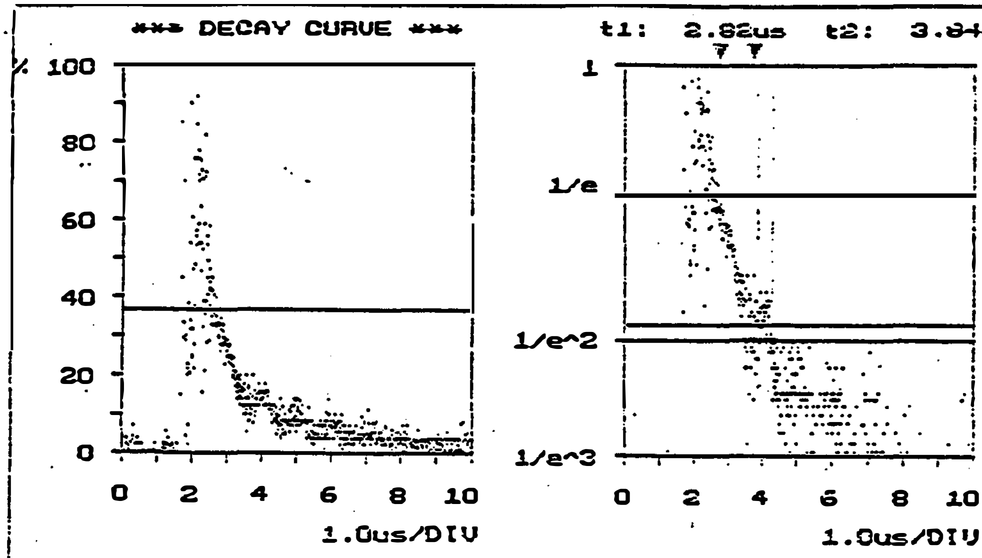
SAMPL P. 1024

AVG. 256

DELAY 0.00ns

TEMP 27 °C

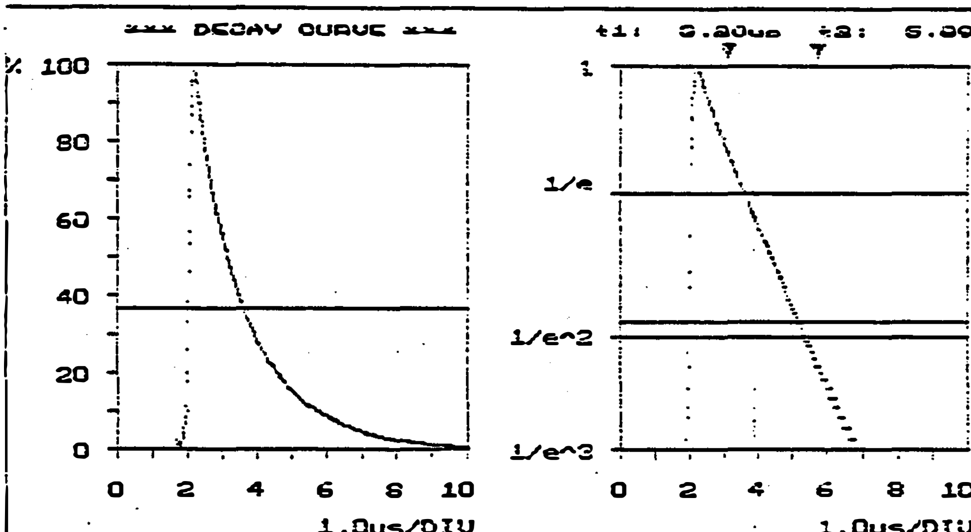
4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END



DATE 1994/02/04
TIME 18:45:17
INPUT RANGE 20 mv
Wafer no: nrel-8
LASER POW L5 (99h)
LASER SEL LD2
INT. TIME 10ns
SAMPL P. 1024
AVG. 256
DELAY 0.00ns
TEMP 27 °C

	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	log
1	+00.0	+00.0	19	20.00 ns	850.47 ns
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END



DATE 1994/02/04
TIME 18:51:54
INPUT RANGE 20 mv
Wafer no: nrel-9
LASER POW L5 (99h)
LASER SEL LD2
INT. TIME 10ns
SAMPL P. 1024
AVG. 256
DELAY 0.00ns
TEMP 27 °C

	X-POSI (mm)	Y-POSI (mm)	PEAK (mv)	LIFETIME 1/e	log
1	+00.0	+00.0	15	1.42 us	1.63 us
2					
3					
4					
5					

4:TIME SET 7:DECY INP 8:PARA INP 9:TITLE 10:END

Raw Data from

Sandia National Laboratories (SNL)

Contact person: Dr. Paul Basore

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: 4 June 1993

to: Bhushan Sopori, NREL

from: Paul Basore, SNL 6213

subject: Cells for Comparison of Lifetime Measurements

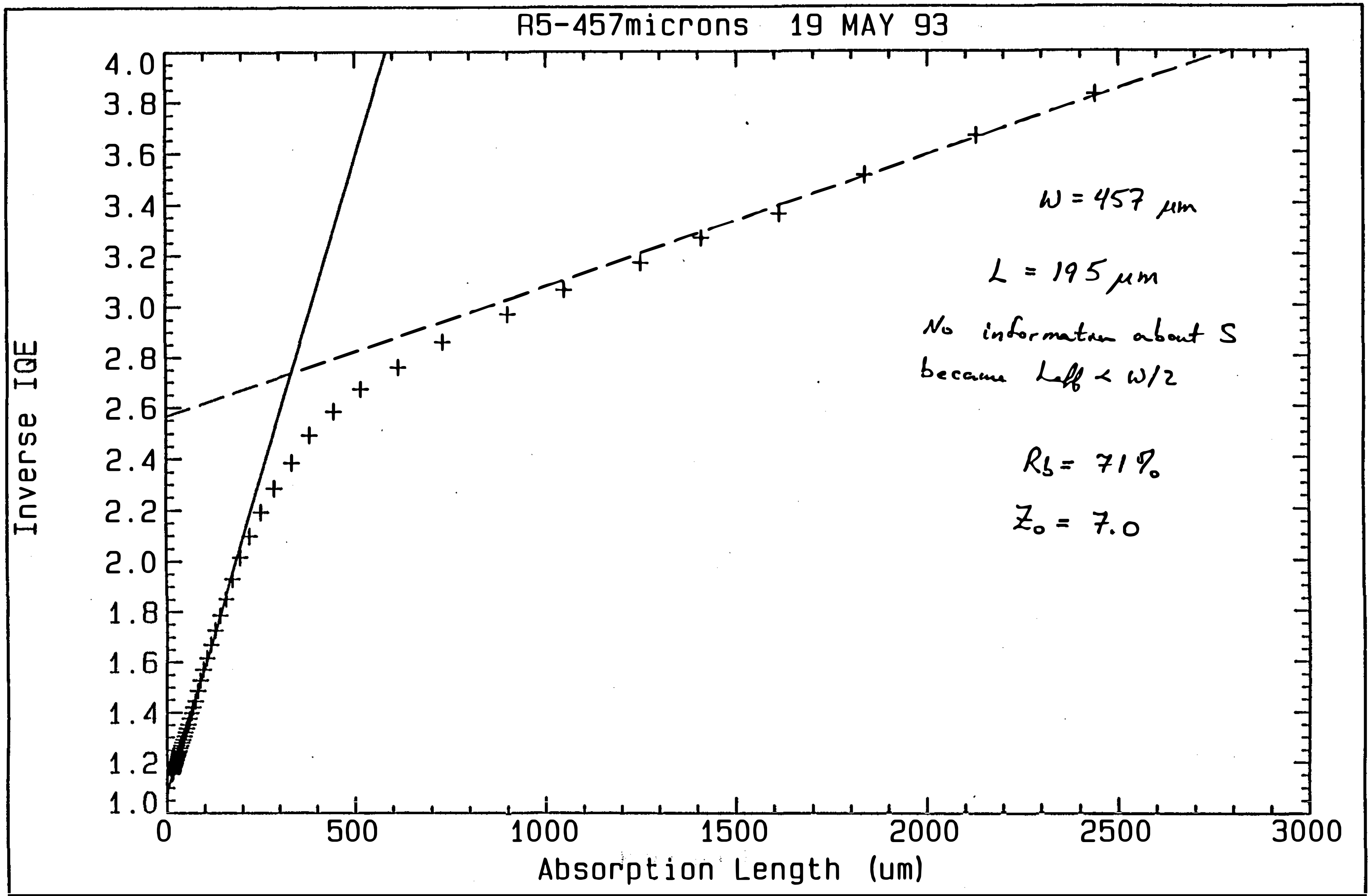
I have sent you a shipment containing six planar 1-cm^2 multicrystalline silicon solar cells fabricated at Georgia Tech, and three 100-mm-diameter monocrystalline silicon wafers each containing eight 4-cm^2 textured cells fabricated in the PDFL. All of the cells have an aluminum-alloy back-surface field. The GIT cells have already been characterized at ECN and they were given to me at the PVSC. The PDFL wafers are three different resistivities: 0.39 Ωcm, 1.77 Ωcm, and 9.85 Ωcm. I characterized the middle two cells on each wafer (cells D and E) to obtain estimates for both diffusion length (L) and back-surface recombination velocity (S).

The attached plots of inverse IQE show the results of my analysis on four of the six GIT cells and six of the PDFL cells. All four GIT cells have a diffusion length sufficiently shorter than the thickness that no meaningful information could be extracted regarding S. The PDFL cells should give S values to within about a factor of two. Table 1 summarized my results. R_b is the internal rear-surface reflectance, and Z_o is the near-bandgap light-trapping thickness multiplier. I also attached a 2D LBIC scan at 820 nm of the region of cell R4 that was used for the IQE analysis. It shows about a ±10% variation in diffusion length over this region.

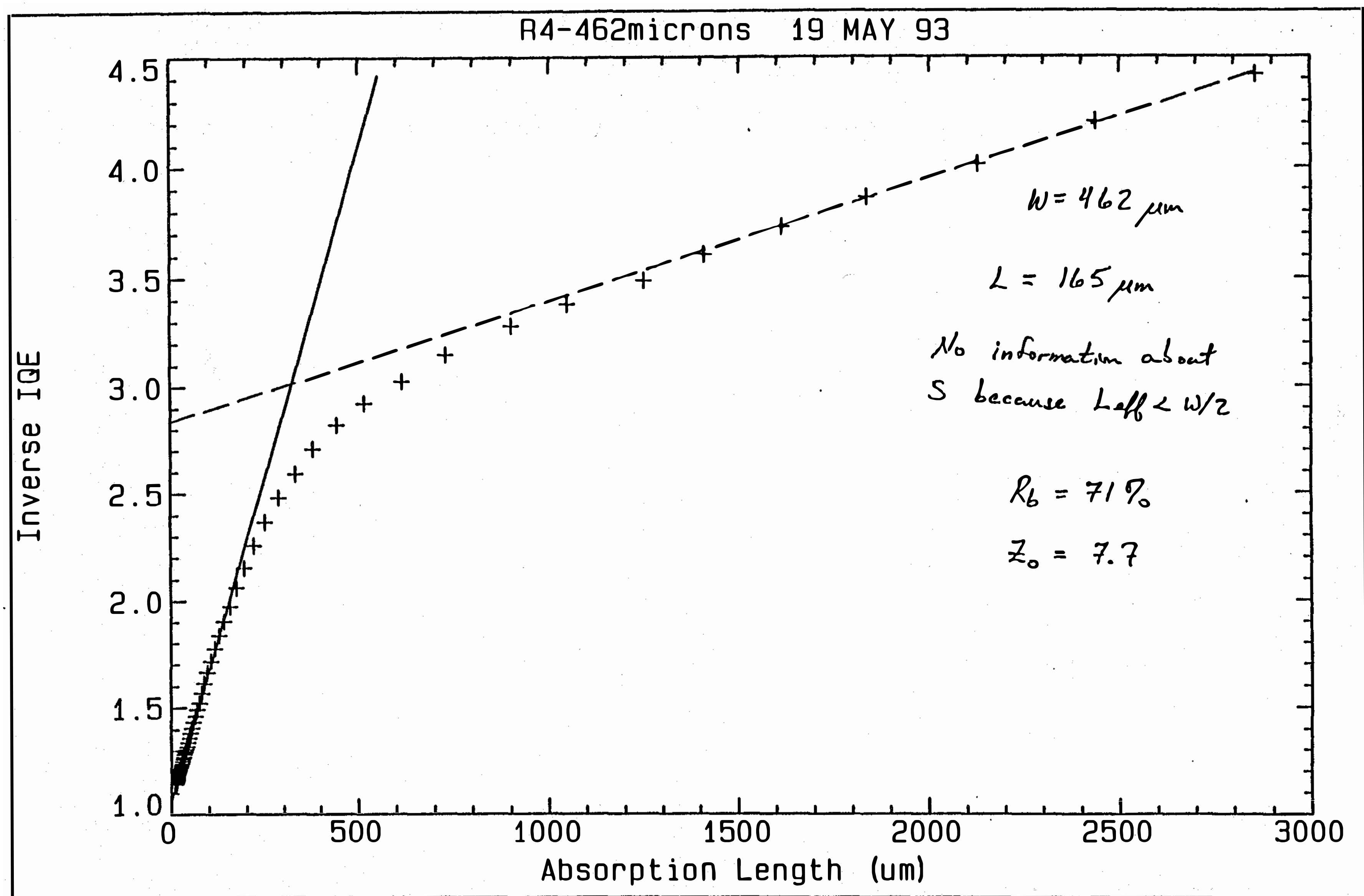
Table 1
Extended Analysis of Internal Quantum Efficiency

Cell ID	ρ(Ωcm)	Thick(μm)	L(μm)	SW/D	R_b(%)	Z_o
R5	??	457	195	??	71	7.0
R4	??	462	165	??	71	7.7
R10	??	460	215	??	66	6.0
R12	??	452	270	??	72	6.2
4D	9.85	586	510	0.36	74	10.1
4E	9.85	586	500	0.32	74	10.0
7D	1.77	468	390	1.25	77	11.6
7E	1.77	468	350	0.50	75	10.6
8D	0.39	322	220	0.62	77	11.5
8E	0.39	322	230	0.73	79	12.7

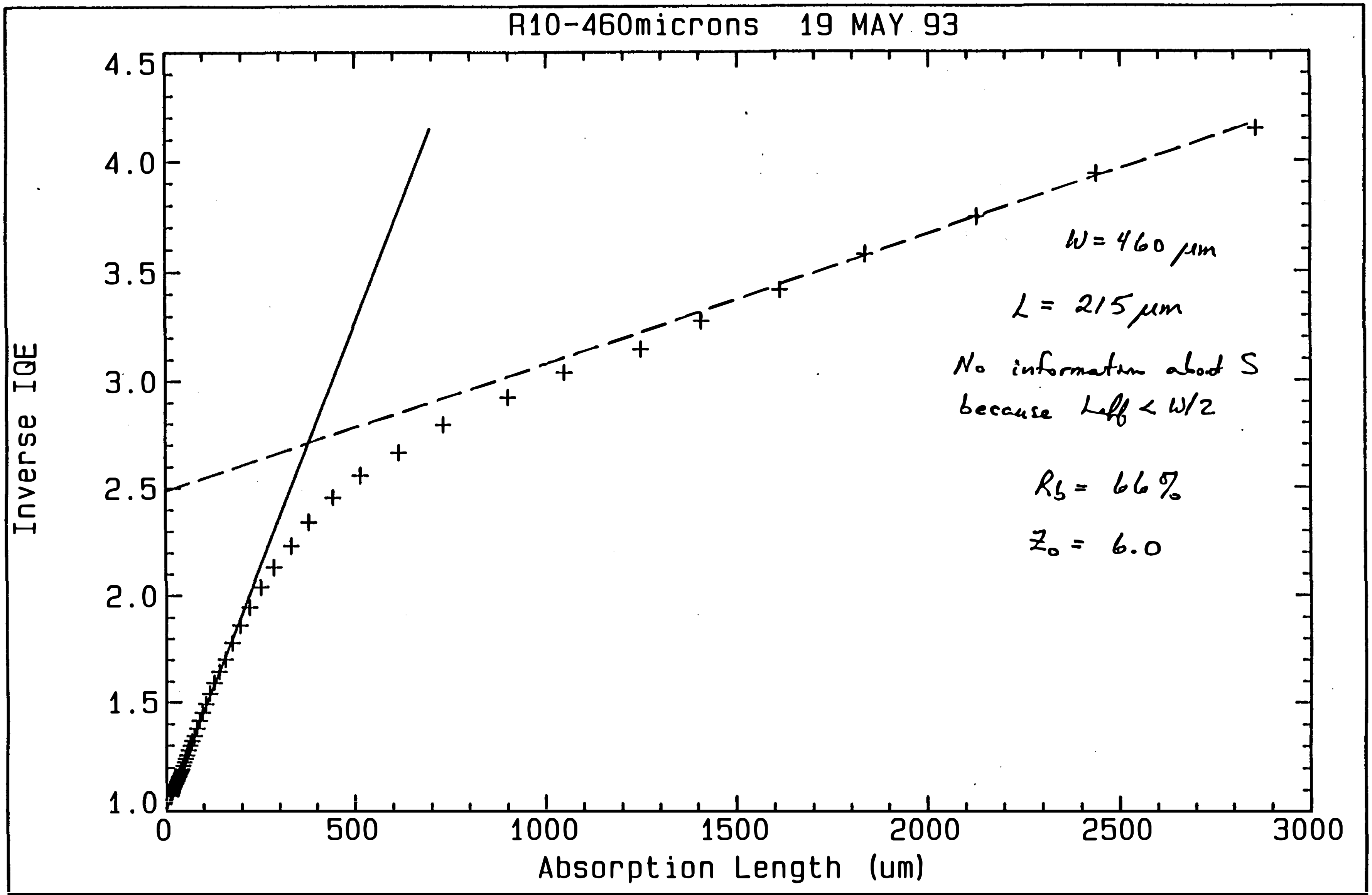
PAB:6213



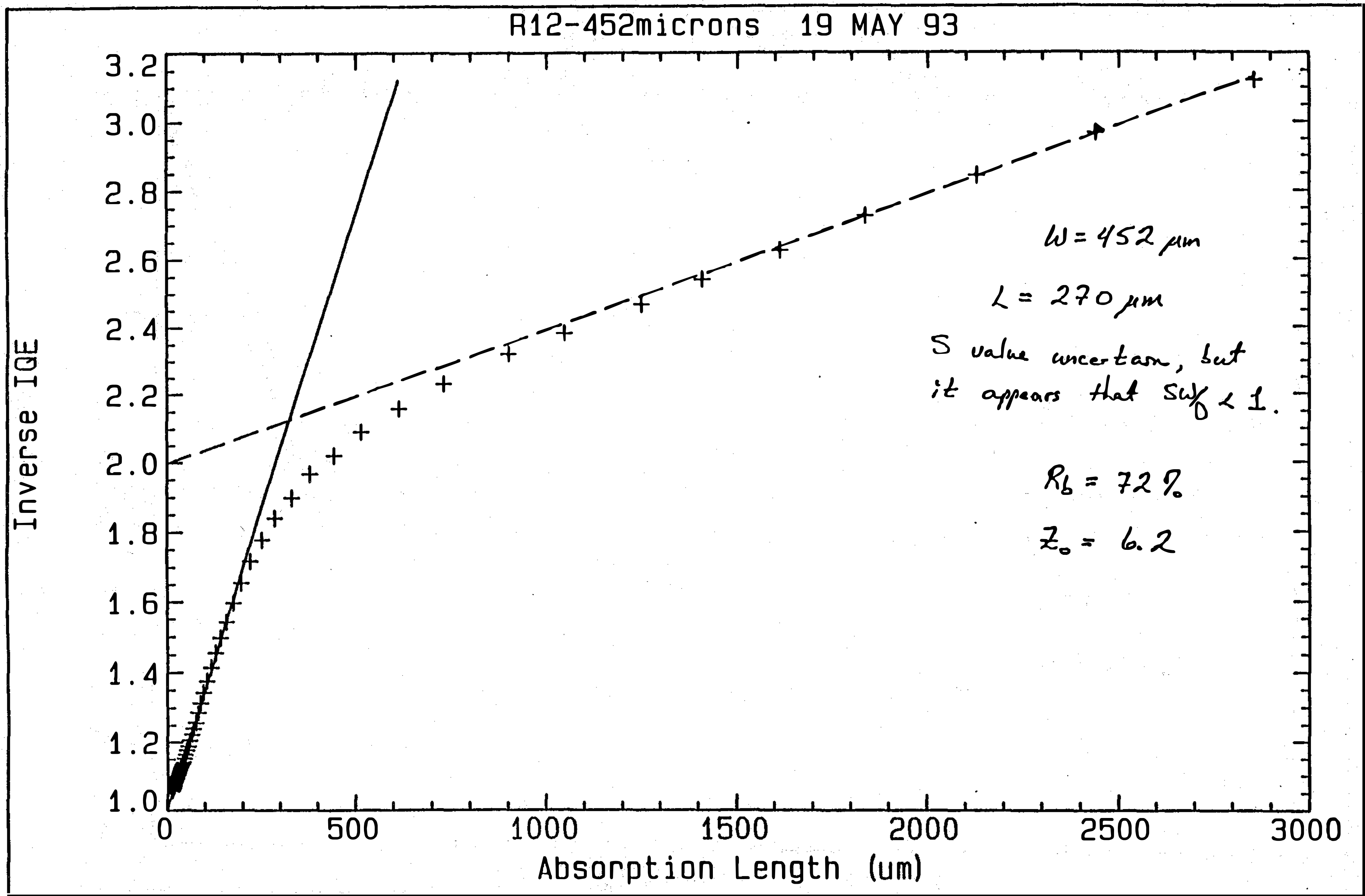
Spectral Response Filename: 93075-02.ASR Reflectance Filename: 93075-02.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 48.1%, Rfe = 28.7%
L(IQE) = 200.2 um, Intcpt = 1.086 W(IQE) = 1943.5 um, Intcpt = 2.563



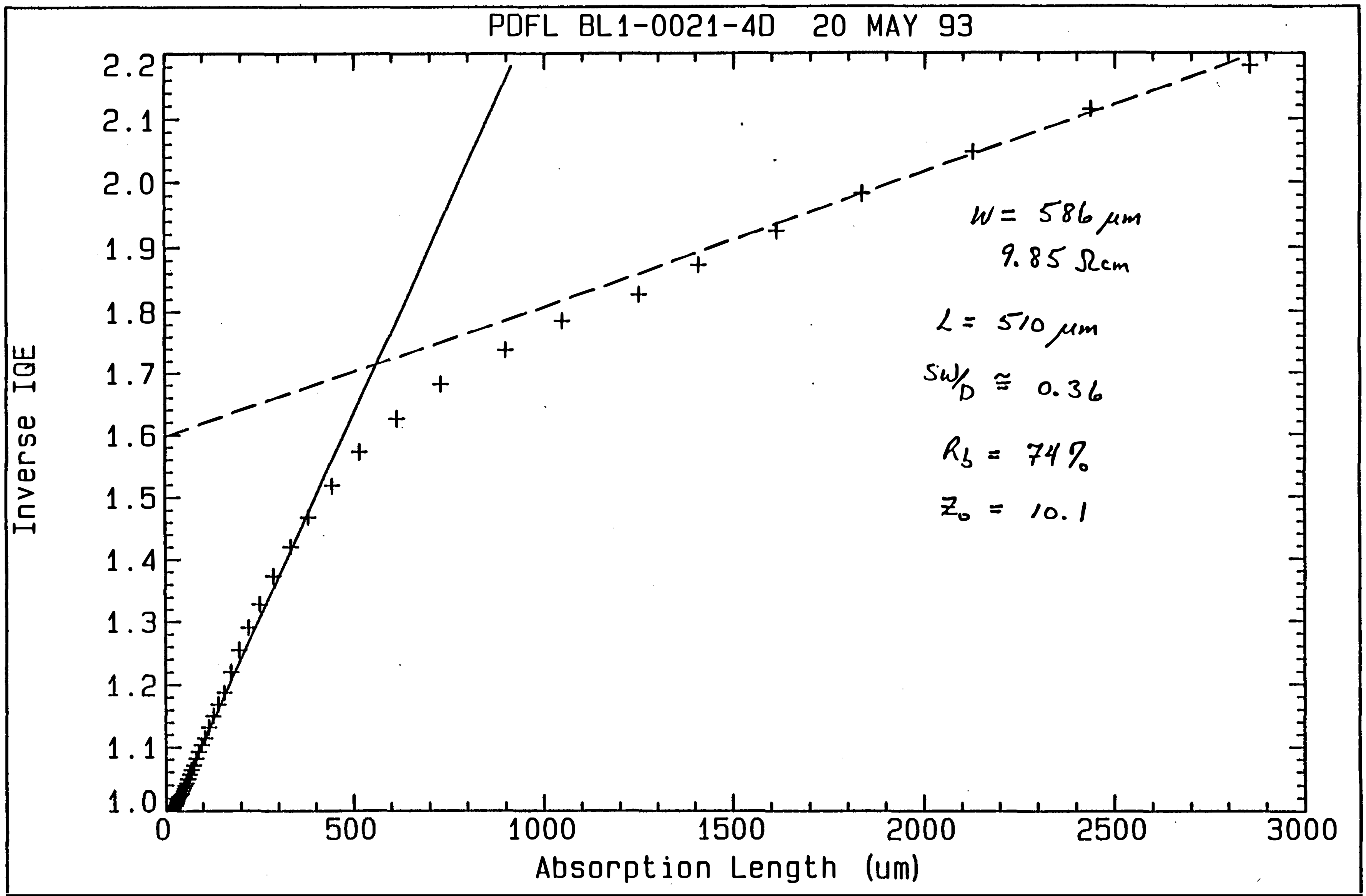
Spectral Response Filename: 93075-01.ASR Reflectance Filename: 93075-01.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 46.4%, Rfe = 31.2%
L(IQE) = 164.9 um, Intcpt = 1.070 W(IQE) = 1792.7 um, Intcpt = 2.838



Spectral Response Filename: 93075-03.ASR   Reflectance Filename: 93075-03.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps   Rsub = 28.4%, Rfe = 5.1%
L(IQE) = 221.8 um, Intcpt = 1.015   W(IQE) = 1689.5 um, Intcpt = 2.485



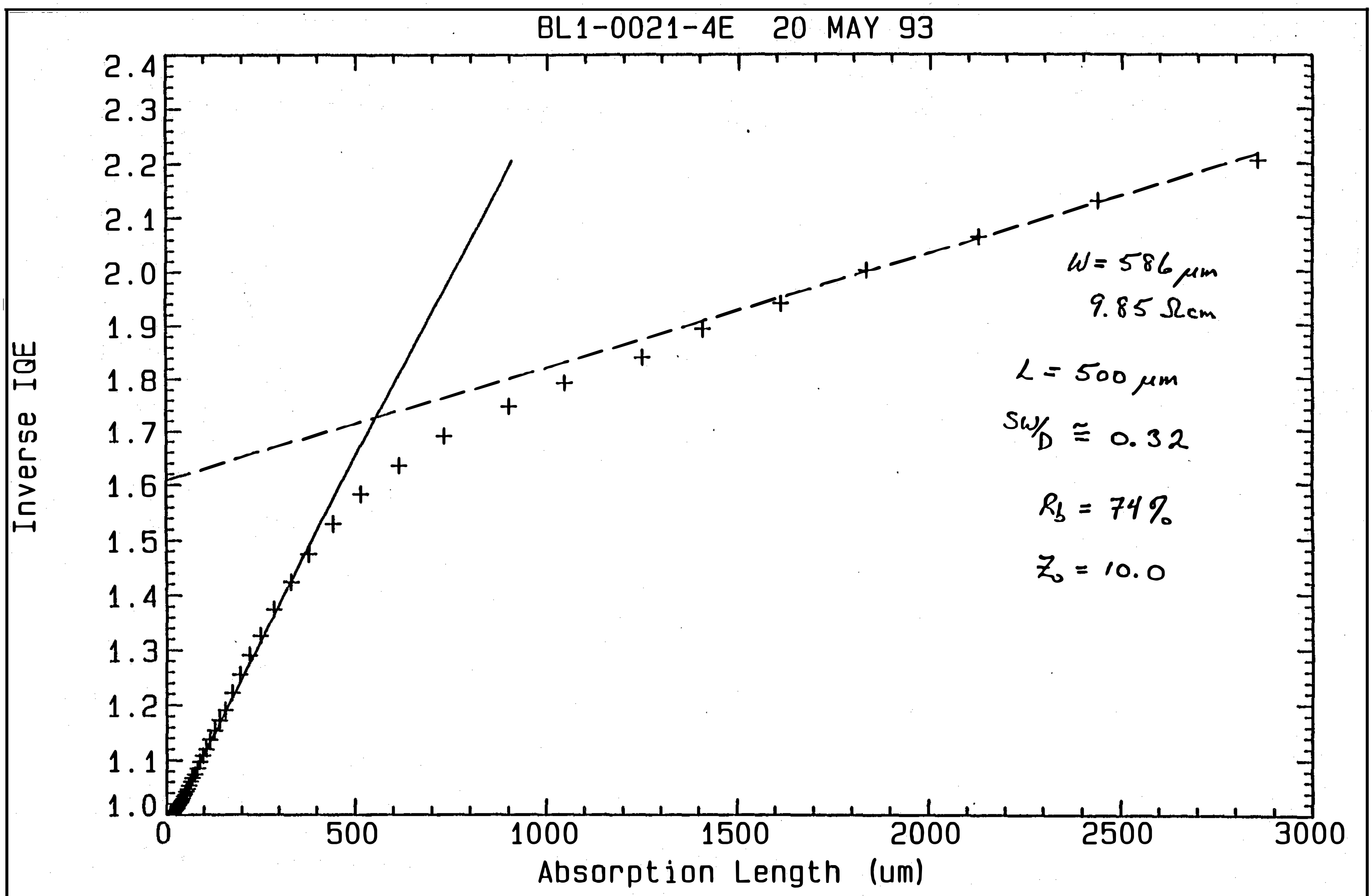
Spectral Response Filename: 93075-04.ASR Reflectance Filename: 93075-04.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 40.2%, Rfe = 6.0%
L(IQE) = 288.4 um, Intcpt = 1.008 W(IQE) = 2516.4 um, Intcpt = 1.997



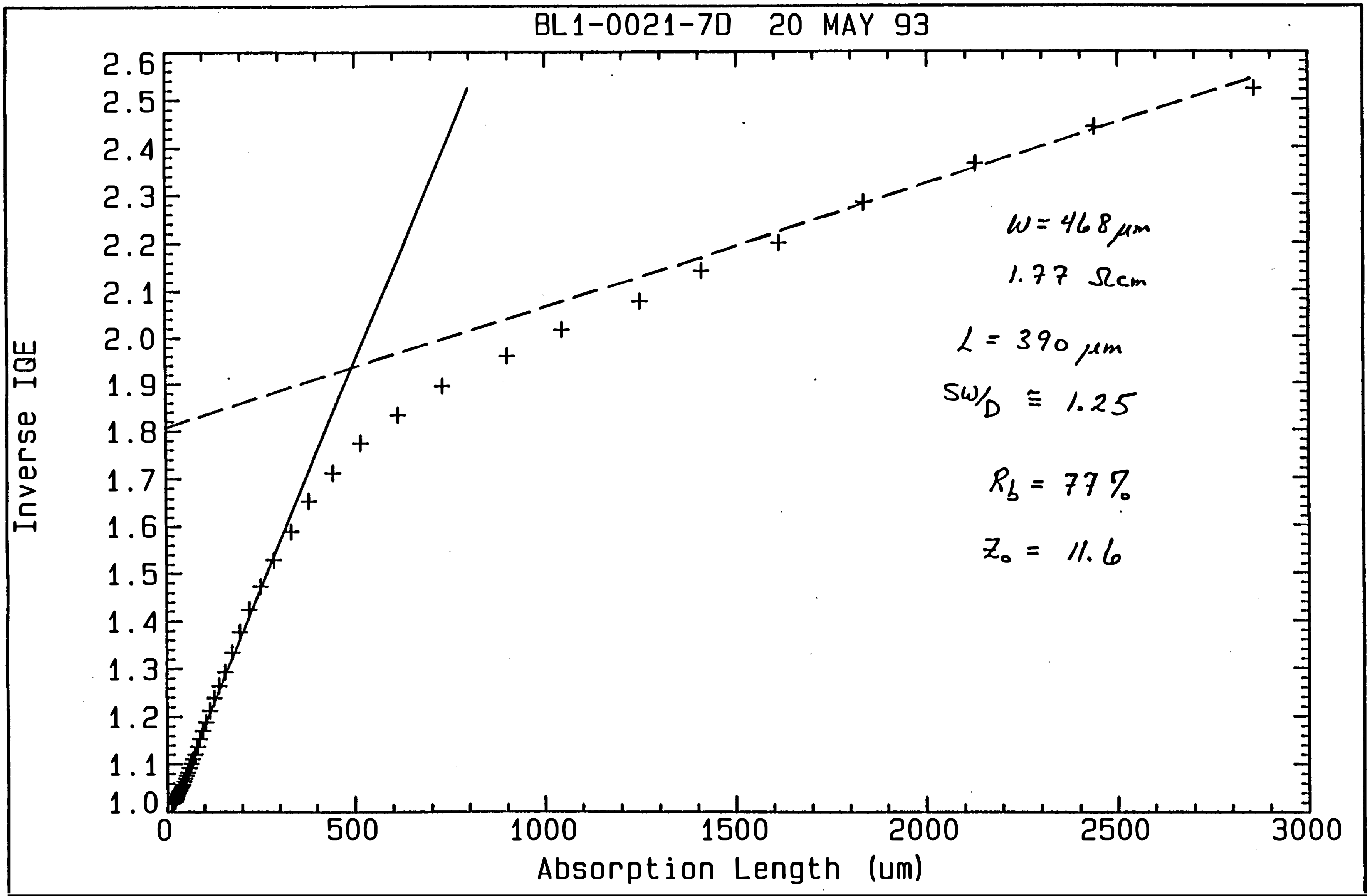
Spectral Response Filename: 93078-01.ASR Reflectance Filename: 93078-01.RFL

Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 24.3%, Rfe = 7.2%

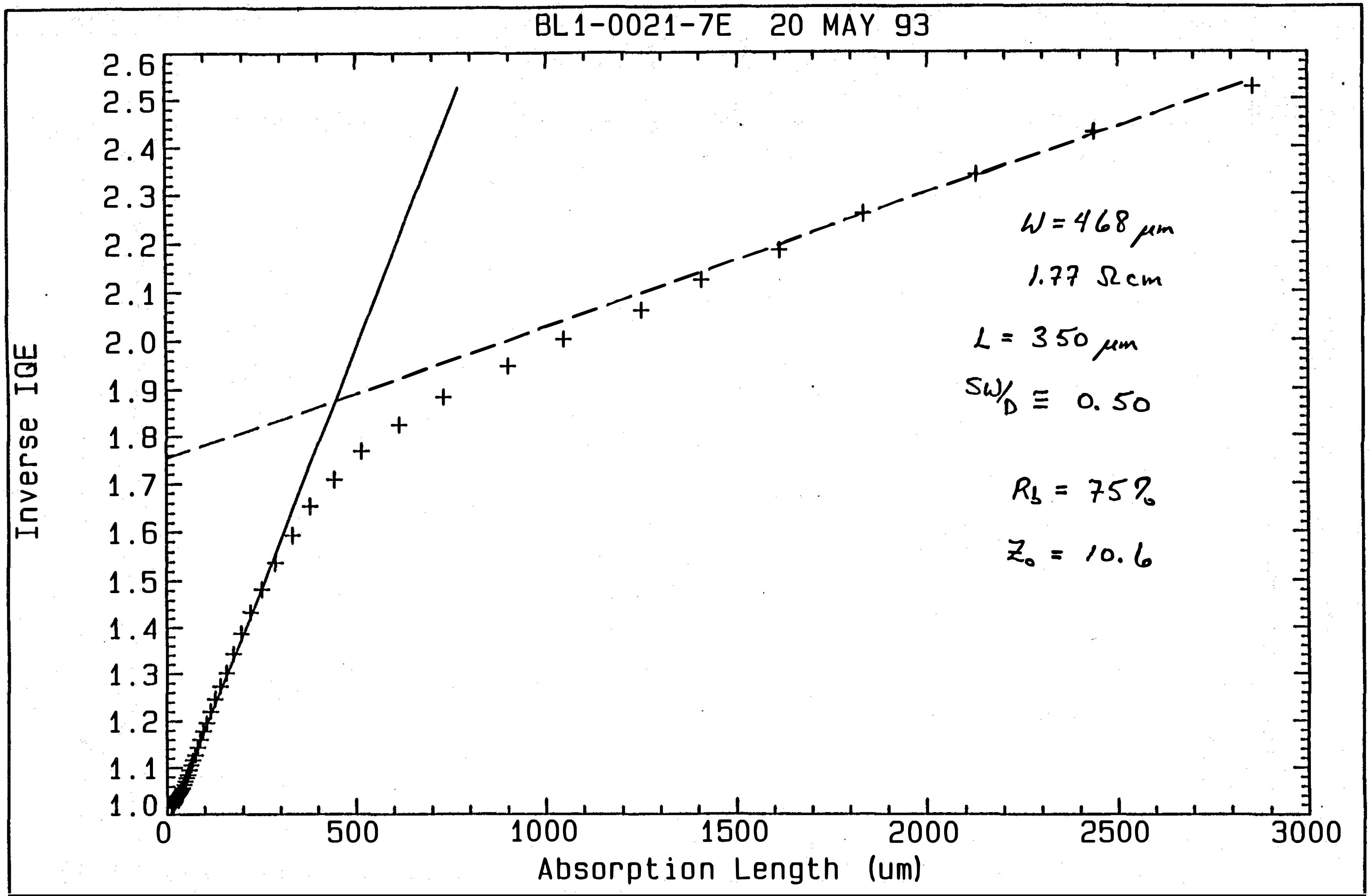
L(IQE) = 758.4 um, Intcpt = 0.977 W(IQE) = 4772.2 um, Intcpt = 1.597



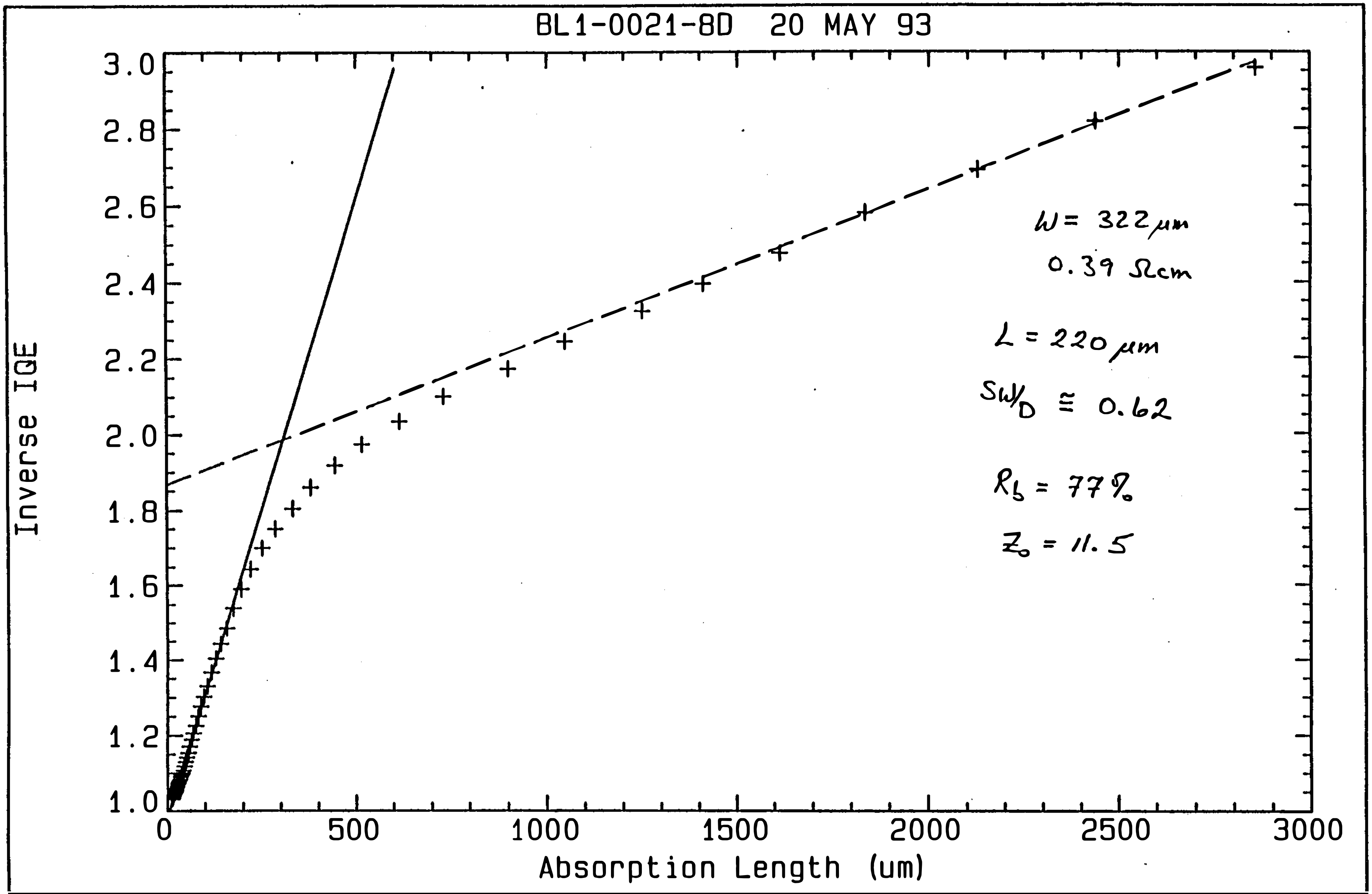
Spectral Response Filename: 93078-02.ASR Reflectance Filename: 93078-02.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 23.8%, Rfe = 7.2%
L(IQE) = 738.5 um, Intcpt = 0.978 W(IQE) = 4690.4 um, Intcpt = 1.608



Spectral Response Filename: 93078-03.ASR Reflectance Filename: 93078-03.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 24.8%, Rfe = 7.3%
L(IQE) = 518.7 um, Intcpt = 0.986 W(IQE) = 3871.0 um, Intcpt = 1.806



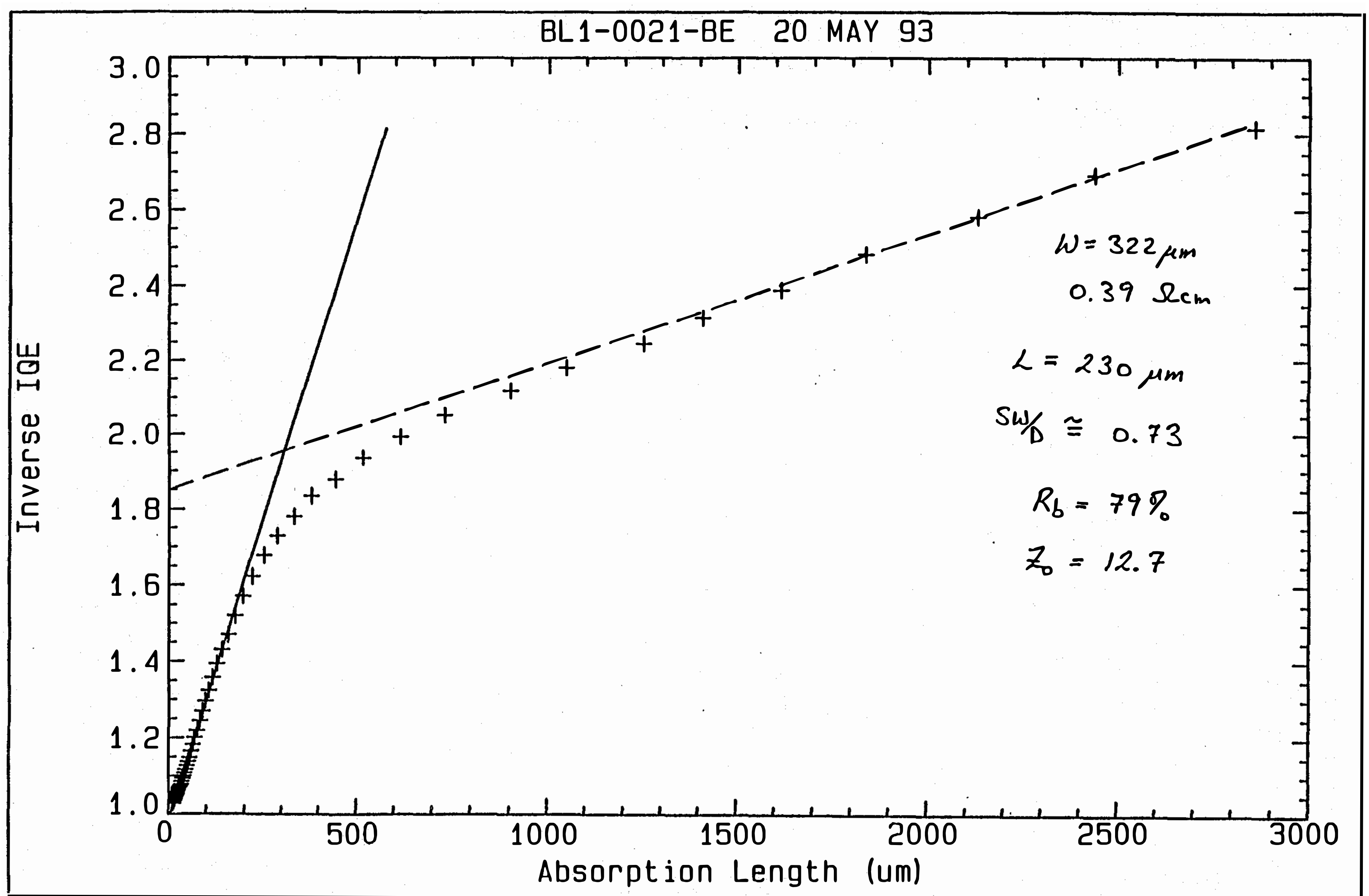
Spectral Response Filename: 93078-04.ASR Reflectance Filename: 93078-04.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps Rsub = 24.3%, Rfe = 7.4%
L(IQE) = 499.6 um, Intcpt = 0.984 W(IQE) = 3629.1 um, Intcpt = 1.752



Spectral Response Filename: 93078-05.ASR   Reflectance Filename: 93078-05.RFL

Wavelength Range: 800 to 1100 nm, 5 nm steps   Rsub = 25.9%, Rfe = 8.0%

L(IQE) = 305.2 um, Intcpt = 0.983   W(IQE) = 2580.4 um, Intcpt = 1.867



Spectral Response Filename: 93078-06.ASR   Reflectance Filename: 93078-06.RFL
Wavelength Range: 800 to 1100 nm, 5 nm steps   Rsub = 26.9%, Rfe = 7.5%
L (IQE) = 313.6 um, Intcpt = 0.984   W (IQE) = 2913.8 um, Intcpt = 1.849

Raw Data from

Georgia Institute of Technology (GIT)

Contact person: Dr. Ajeet Rohatgi

NREL Round Robin Cell Data

Cell ID	V_{oc} mV/cm²	J_{sc} mA/cm²	CFF	Efficiency %	τ_{OCD} µs	L_{IQE} microns
1CB	587.2	21.72	.432	5.5	12	158
2CB	581.4	16.6	.304	2.9	8	138
3CB	592.5	21.4	.371	4.7	20	218
4CB	592.3	21.7	.365	4.7	23	273
5CB	603.9	31.8	.431	8.3	30	
6CB	610	32.6	.367	7.3	23	258
7CB-1	571.2	36.9	.733	16.3		625
7CB-2	579.5	37.2	.772	16.6		
8CB-1	614.1	36.6	.797	17.9		590
8CB-2	621.0	36.5	.794	18.0		
9CB-1	646.6	35.7	.796	18.3		298
9CB-2	648.6	35.4	.803	18.5		

Cells 7cb - 9cb are from 4" dia. wafers with 2cm X 2cm cells. The remainder are 1cm X 1cm multicrystalline cells.

Raw Data from

Netherlands Energy Research Foundation (ECN)

Contact person: Dr. Rob Steeman

Results of the LBICD measurements on the monocrystalline τ/L Round-Robin cells

Peter Lölgen

The description of the Light Beam Induced Current Decay (LBICD) measurement technique (also sometimes called: light-induced Short-circuit Current Decay SCD method) is given in the report we presented at the Diffusion length workshop in january 1993 in Phoenix. A more detailed description is given in my thesis in chapter 3 and in several papers (eg. A.R. Burgers, P. Lölgen, J.A. Eikelboom, C. Leguijt, R.A. Steeman, W.C. Sinke, Proc. 12th EC PVSEC, p.504, 1994).

The measurements were performed for 3 or 4 different wavelengths, with and without 0.5 sun white light bias illumination, with a moderate spot-size of 0.2 cm^2, because the cells are expected to be homogeneous, at laser intensity of 5 mW. The calculations of the absorption coefficient were performed by the expression given by Swimm and Dumas. For the evaluation of the current transient we first fitted the entire decay curve for every wavelength, from which we obtain the effective back-surface recombination velocity S, the bulk diffusion length L, the effective lifetime τ_1 (which is influenced by both S and L) and the ratio between the steady state signal and the intercept of the exponent with t=0, Y (which contains the information to separate S and L, see report).
Then the obtained values for the effective lifetime τ_1 and the decay ratio Y were used in the intercept method to extract S and L. This enables to check whether the calculated wavelength dependence of Y is in agreement with the measured one, which gives an indication if the input-parameters like the sample thickness W, diffusion coefficient D and the back surface reflectivity R to describe the model are correct.

The input-parameters D, W, R:

The diffusion coefficient D for the mono cells was given:
for wafer 9CB-D and E, D=25.1 cm^2/s (0.39 Ωcm),
for wafer 8CB-D and E, D=32.6 cm^2/s (1.77 Ωcm),
for wafer 7CB-D and E, D=35.1 cm^2/s (9.85 Ωcm).

We determined the thickness of the wafers by an inductive gauge and we saw that the thickness varied considerably over the wafer. They were all thicker in the middle than at the sides varying 20% eg. for wafer 9CB from 260 µm to 330 µm in the middle (with the same order for the other two samples). So we tried to determine the thickness directly on the cells which were to measure. This of course bares the problem that you measure always with the back-metallisation and it is impossible to determine the actual Si thickness. However we estimated the back metallisation thickness and got a value for the thickness. In the analysis we will show the influence of an error in the thickness.

The back surface reflection is another parameter which the LBICD method needs as an input, because one can extract only two parameters out of a current transient, which enables the determination of S and L. Since the cells are covered with a full evaporated metal on the back, probably aluminium we have two possibilities. One is there is a sharp Si-Al interface, so no Al-BSF is formed by alloying, which would lead to a back surface reflection coefficient of around R=0.9. The other possibility is that an Al-BSF is formed by alloying, which results in a rough Al/Si-alloy - Si interface with an back surface reflection coefficient of around R=0.7 (see A. Rohatgi, P. Sana, J. Salami, Proc. 11th EC PVSEC, p.159, 1992). Since we do not know if an Al-BSF is formed (although the measurements indicate that a thin few µm thick BSF is formed) we used both extremes for our calculations to show the influence of an error in R on the results.

Results:

Cell 9CB-D:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D=25.1 cm^2/s, cell thickness W = 300 µm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (µs)	bulk diff. length L (µm)	surf. rec. velocity S (cm/s)
995 (see Fig.1 and 2)	4.71	230	2130
1009	4.75	228	2240
1023	4.80	224	2100
1037	4.64	269	3150
with bias			
995 + bias	4.77	227	2010
1009 + bias	4.73	225	2250
1023 + bias	4.72	243	2560
1037 + bias	4.78	230	2230

In Fig.1 and Fig.2 the measured data, the fit and the residue of a entire decay curve fit is shown.
In Fig.3 the logarithm of the measured signal without background-substraction is shown. In Fig.4 the second derivative of the measured signal, divided by the first derivative is shown. This plot is to check whether the decay really becomes exponential, without an influence of a constant background (see the plateau between 18 and 30 µs). Fig.5 shows the Y values for the four wavelengths, together with calculated S and L combinations which are possible with the effective lifetime τ_1.
In Fig.6 the range of S-values is shown for which the Chi^2 is below 1.

Taking W=300 µm, D=25.1cm^2/s, R=0.9 this results in:

Without bias:
9D: L = 220 - 260 µm, S = 2200 - 2800 cm/s, τ_{1av} = 4.73 ± 0.05 (average decay time).

With bias illumination, 1/2 sun:
9D-bias: L = 210 - 260 µm, S = 2000 - 2800 cm/s, τ_{1av} = 4.75 ± 0.05

If we assume R=0.7 the results change into:

Without bias:
9D: L = 240 - 280 µm, S = 2600 - 3100 cm/s

With bias illumination, 1/2 sun:
9D-bias: L = 230 - 280 µm, S = 2300 - 3000 cm/s

Cell 9CB-E:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D=25.1 cm^2/s, cell thickness W = 300 μm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (μs)	bulk diff. length L (μm)	surf. rec. velocity S (cm/s)
995	4.97	227	1720
1009	4.95	232	1990
1023	5.05	231	1830
1037	4.94	256	2330
with bias			
995 + bias	4.98	229	1740
1009 + bias	4.97	231	1950
1023 + bias	5.09	225	1700
1037 + bias	4.93	248	2330

The τ_1 values and Y values (not listed) obtained out of this fit were used in the intercept method. Taking W=300 μm, D=25.1cm^2/s, R=0.9 this results in:

Without bias:
9E: L = 220 - 260 μm, S = 1800 - 2300 cm/s, τ_{1av} = 4.98 ± 0.05 (average decay time).

With bias illumination, 1/2 sun:
9E-bias: L = 210 - 260 μm, S = 1600 - 2300 cm/s, τ_{1av} = 4.99 ± 0.05

If we assume R=0.7 the results change into:

Without bias:
9E: L = 230 - 280 μm, S = 1950 - 2500 cm/s

With bias illumination, 1/2 sun:
9E-bias: L = 230 - 280 μm, S = 1900 - 2500 cm/s

Cell 8CB-D:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D=32.6 cm^2/s, cell thickness W = 460 µm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (µs)	bulk diff. length L (µm)	surf. rec. velocity S (cm/s)
995	8.08	342	2340
1009	7.98	347	2520
1023	8.07	363	2610
1037	8.16	378	2650
with bias			
995 + bias	8.49	323	1730
1009 + bias	8.23	347	2230
1023 + bias	8.20	349	2290
1037 + bias	8.26	357	2320

The τ_1 values and Y values (not listed) obtained out of this fit were used in the intercept method. Taking W=460 µm, D=32.6 cm^2/s, R=0.9 this results in:

Without bias:
8D: L = 330 - 390 µm, S = 2200 - 2900 cm/s, τ_{1av} = 8.07 ± 0.05

With bias illumination, 1/2 sun:
8D-bias: L = 320 - 380 µm, S = 1800 - 2400 cm/s, τ_{1av} = 8.25 ± 0.05

If we assume R=0.7 the results change into:

Without bias:
8D: L = 350 - 410 µm, S = 2400 - 3100 cm/s

With bias illumination, 1/2 sun:
8D-bias: L = 340 - 380 µm, S = 2200 - 2600 cm/s

Cell 8CB-E:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D=32.6 cm^2/s, cell thickness W = 460 μm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (μs)	bulk diff. length L (μm)	surf. rec. velocity S (cm/s)
995	7.96	319	2170
1009	7.99	327	2260
1023	8.06	340	2340
1037	8.19	355	2360
with bias			
995 + bias	8.05	317	2050
1009 + bias	7.91	333	2430
1023 + bias	8.09	343	2340
1037 + bias	8.34	345	2090

The τ_1 values and Y values (not listed) obtained out of this fit were used in the intercept method. Taking W=460 μm, D=32.6 cm^2/s, R=0.9 this results in:

Without bias:
8E: L = 320 - 370 μm, S = 2000 - 2700 cm/s, τ_{1av} = 8.05 ± 0.05

With bias illumination, 1/2 sun:
8E-bias: L = 300 - 360 μm, S = 1800 - 2600 cm/s, τ_{1av} = 8.10 ± 0.05

If we assume R=0.7 the results change into:

Without bias:
8E: L = 330 - 390 μm, S = 2200 - 2900 cm/s

With bias illumination, 1/2 sun:
8E-bias: L = 330 - 390 μm, S = 2200 - 2800 cm/s

Cell 7CB-D:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D = 35.1 cm^2/s, cell thickness W = 560 μm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (μs)	bulk diff. length L (μm)	surf. rec. velocity S (cm/s)
995	10.25	333	2100
1009	10.06	363	2920
1023	10.02	377	3310
with bias			
995 + bias	11.02	336	2930
1009 + bias	10.55	361	2300
1023 + bias	10.34	384	2290

The τ_1 values and Y values (not listed) obtained out of this fit were used in the intercept method. Taking W=560 μm, D=35.1 cm^2/s, R=0.9 this results in:

Without bias:
7D: L = 340 - 360 μm, S = 2000 - 2200 cm/s, τ_{1av} = 10.11 ± 0.05

With bias illumination, 1/2 sun:
7D-bias: L = 350 μm, S = 1800 cm/s, τ_{1av} = 10.64 ± 0.05 (not a good fit)

If we assume R=0.7 the results change into:

Without bias:
7D: L = 360 μm, S = 2200 cm/s (not a good fit)

With bias illumination, 1/2 sun:
7D-bias: L = 350 μm, S = 1700 cm/s (not a good fit)

Cell 7CB-E:

In the following Table you see the results of the fit to the entire decay transient for every wavelength. Taking the following input-parameters:
Diff. coeff. D = 35.1 cm^2/s, cell thickness W = 560 μm, back-surface reflection R = 0.9.

wavelength (nm) [no bias]	decay-time τ_1 (μs)	bulk diff. length L (μm)	surf. rec. velocity S (cm/s)
995	10.46	330	1850
1009	10.31	342	2210
1023	10.22	362	2680
with bias			
995 + bias	10.70	341	1850
1009 + bias	10.58	350	2090
1023 + bias	10.43	373	2620

The τ_1 values and Y values (not listed) obtained out of this fit were used in the intercept method. Taking W=560 μm, D=35.1 cm^2/s, R=0.9 this results in:

Without bias:
7E: L = 330 - 350 μm, S = 1600 - 1900 cm/s, τ_{1av} = 10.33 ± 0.05

With bias illumination, 1/2 sun:
7E-bias: L = 330 - 350 μm, S = 1500 - 1800 cm/s, τ_{1av} = 10.57 ± 0.05

If we assume R=0.7 the results change into:

Without bias:
7E: L = 340 - 350 μm, S = 1700 - 1900 cm/s

With bias illumination, 1/2 sun:
7E-bias: L = 340 - 350 μm, S = 1600 - 1800 cm/s

Influence of an error in W:

We take cell 8CB-D as an example of which we determined a thickness of W=460 µm. If the thickness is 420 µm instead of 460 µm the values for S and L change into the following values:

W=420 µm: L = 300 - 330 µm, S = 1100 - 1400 cm/s (with R=0.9 and D=32.6).
[W=460 µm: L = 330 - 390 µm, S = 2200 - 2900 cm/s]

As one can see, a strong error in the thickness also causes a large change in S and L.
So if the thicknesses of the participants of this Round-Robin have large differences the results should be recalculated with a uniform thickness. The same holds for the other input parameters D and R.

Discussion and Conclusion:

It was possible to perform good LBICD-measurements on the monocrystalline Round Robin cells.
The results show that the two analysis methods, the entire decay curve fitting and the intercept method, are in good agreement with each other. For some samples a slight drift in S and L as a function of the wavelength is observed in the entire decay fit method, which can be an indication of a not correctly chosen input-parameter like the thickness.
The cells seem to have a thin BSF which gives reasonable passivation of around S = 2000 - 3000 cm/s and which is of course dependent on the base doping. This might be the reason why the two cells of 7CB have the lowest back surface recombination.

Enlargement of the signal showed that there is a small influence of ringing on the fast initial decay of the current transients for these 4 cm^2 cells which can not be seen in the full decay curve. Reducing the size of the cells results in a smaller ringing frequency, which however had no influence on the fit results. So we measured with the large cells.

Fig 1.

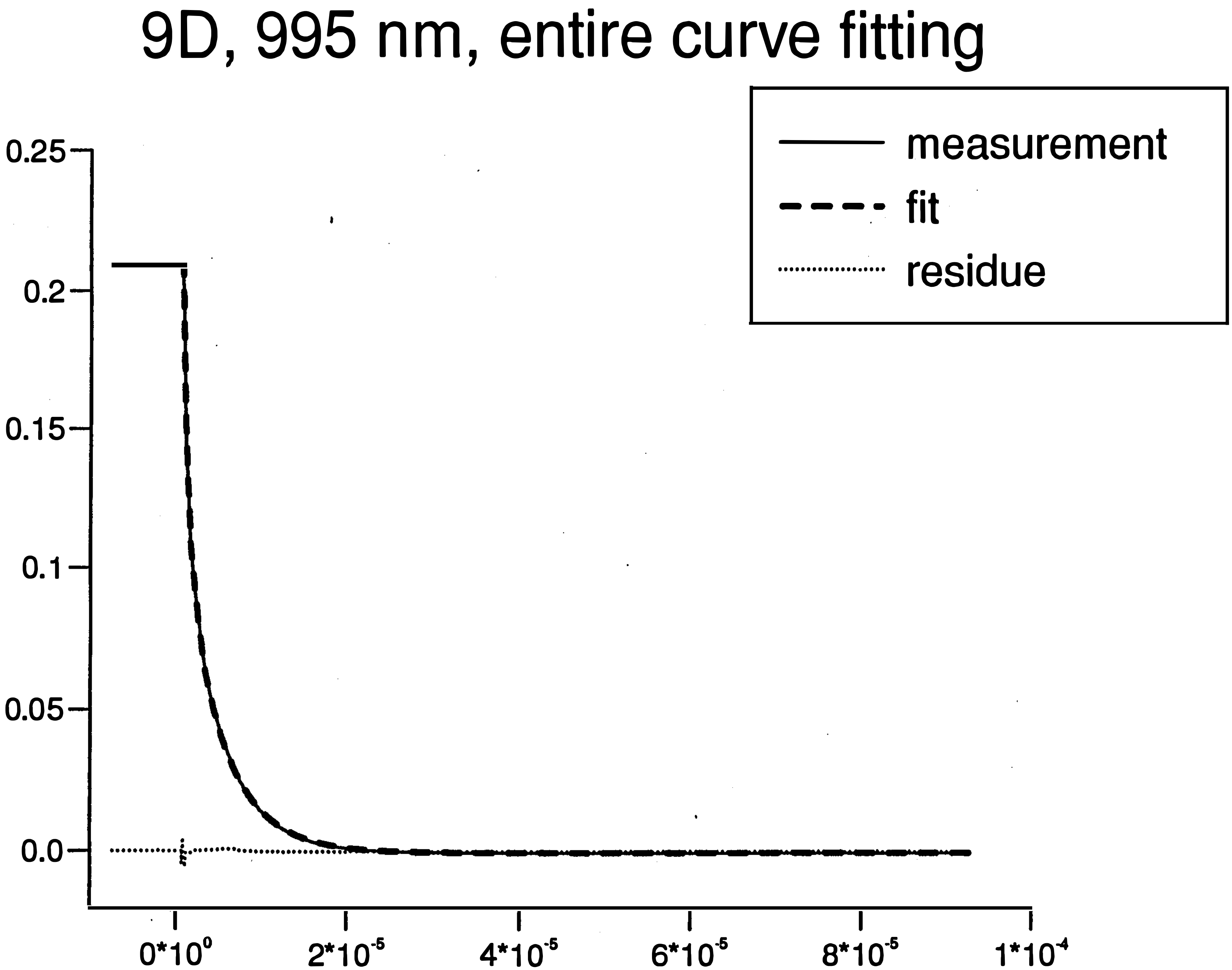

9D, 995 nm, entire curve fitting
measurement
fit
residue
0.25
0.2
0.15
0.1
0.05
0.0
0*10^0
2*10^-5
4*10^-5
6*10^-5
8*10^-5
1*10^-4

Fig. 2

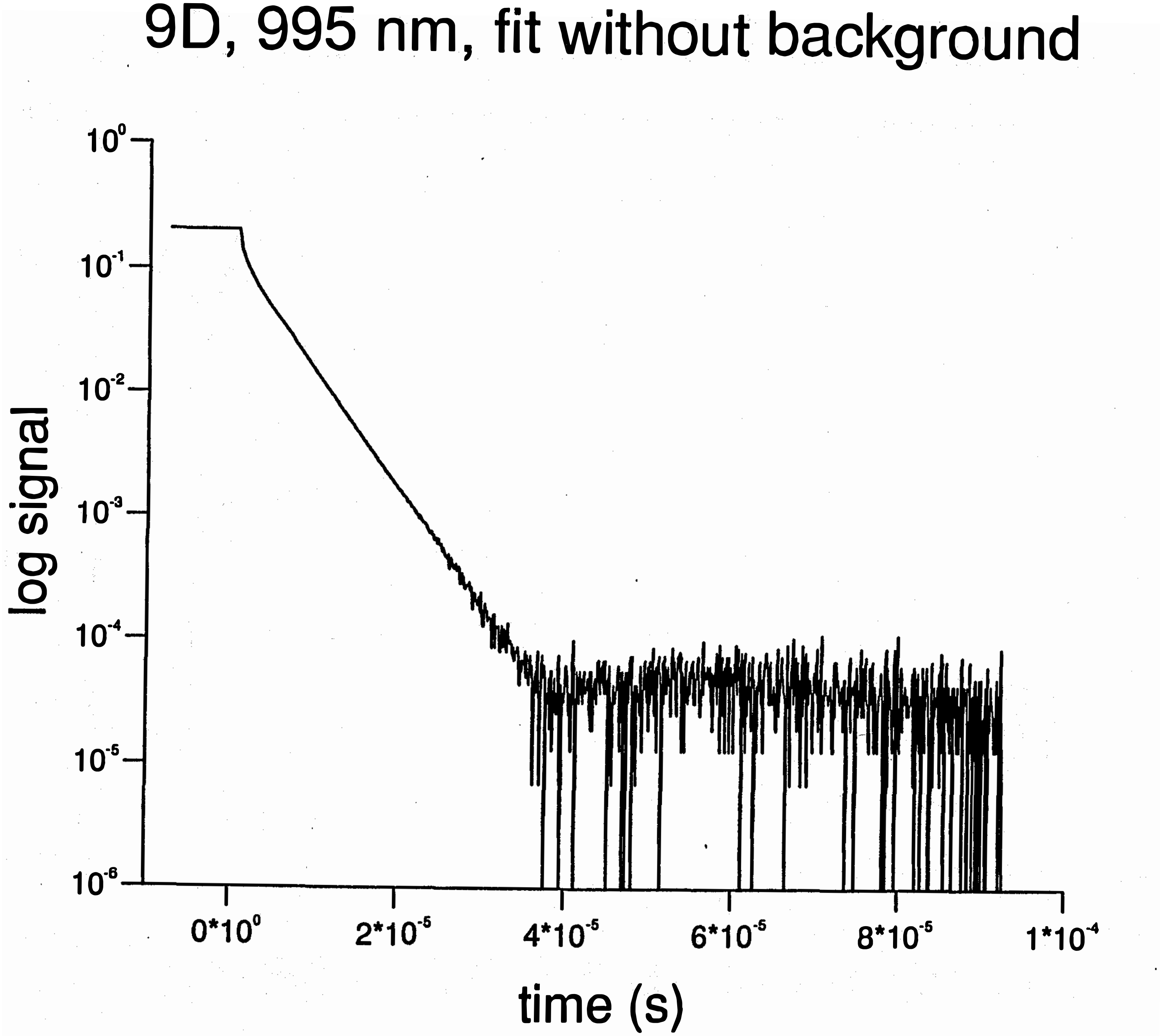

9D, 995 nm, fit without background
log signal
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0*10^0
2*10^-5
4*10^-5
6*10^-5
8*10^-5
1*10^-4
time (s)

Fig 3

log signal of 9D, wavelength=995 nm

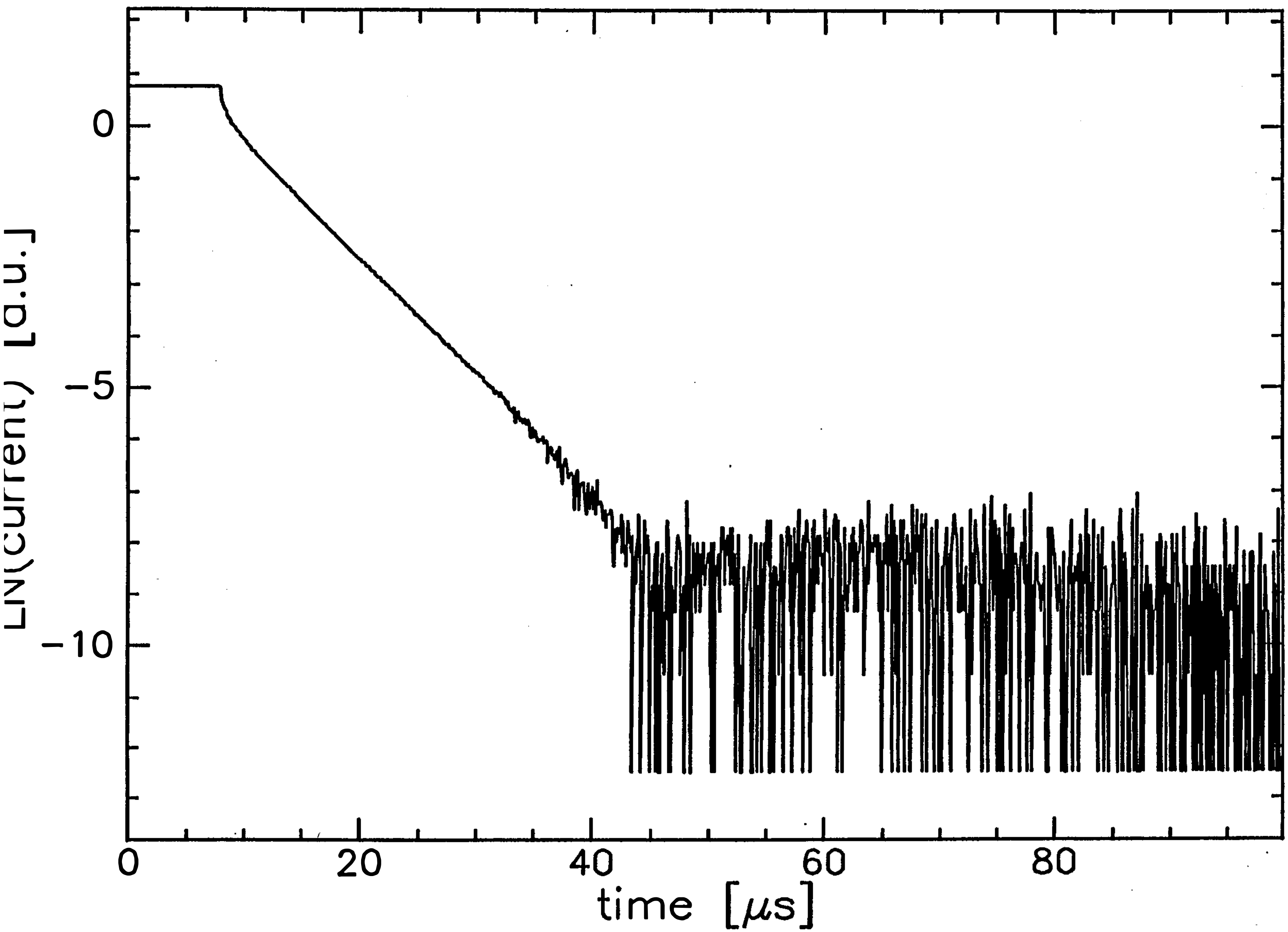
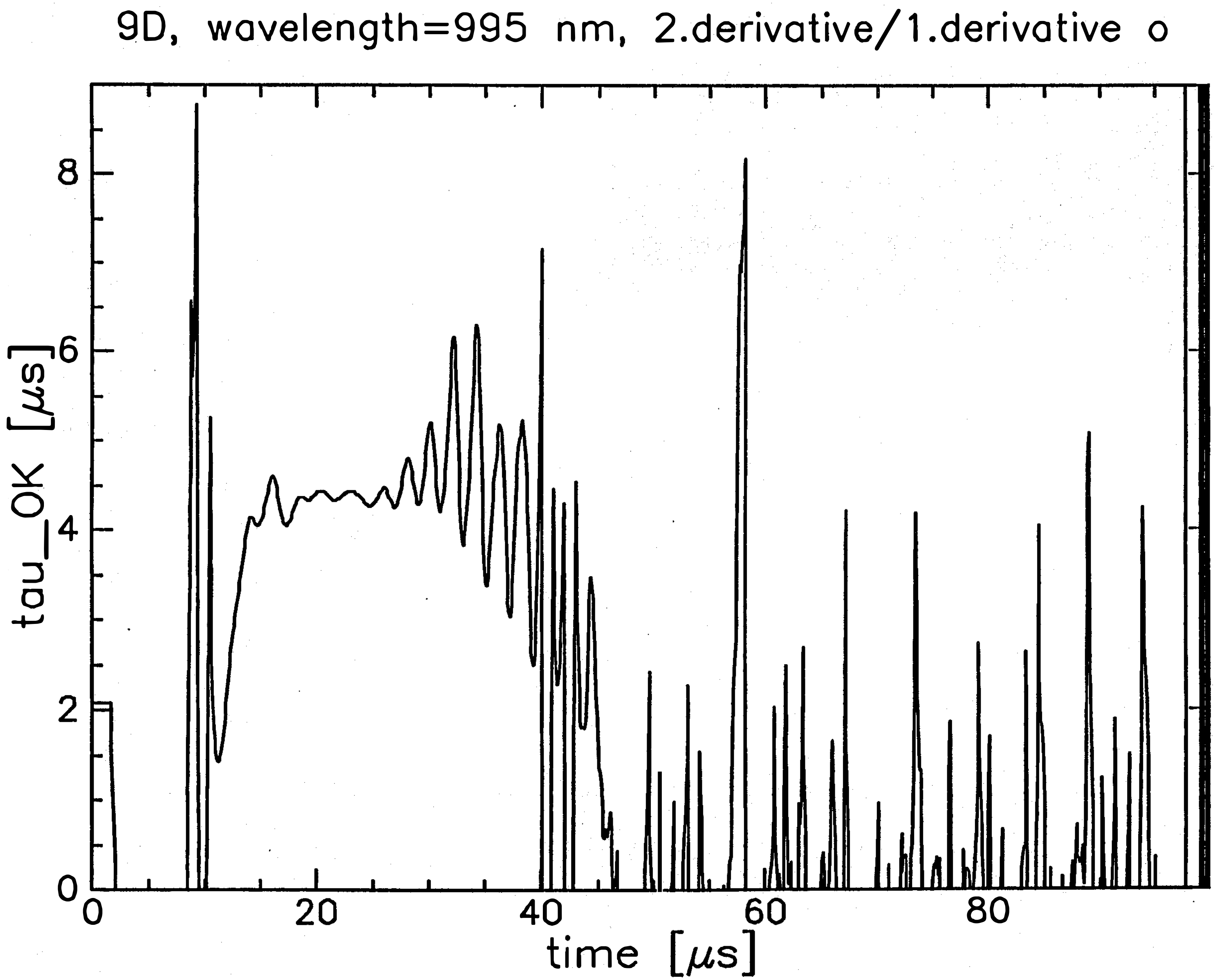


Fig 4



9D, wavelength=995 nm, 2.derivative/1.derivative o
tau_OK [μs]
time [μs]
0
2
4
6
8
0
20
40
60
80

Fig. 5

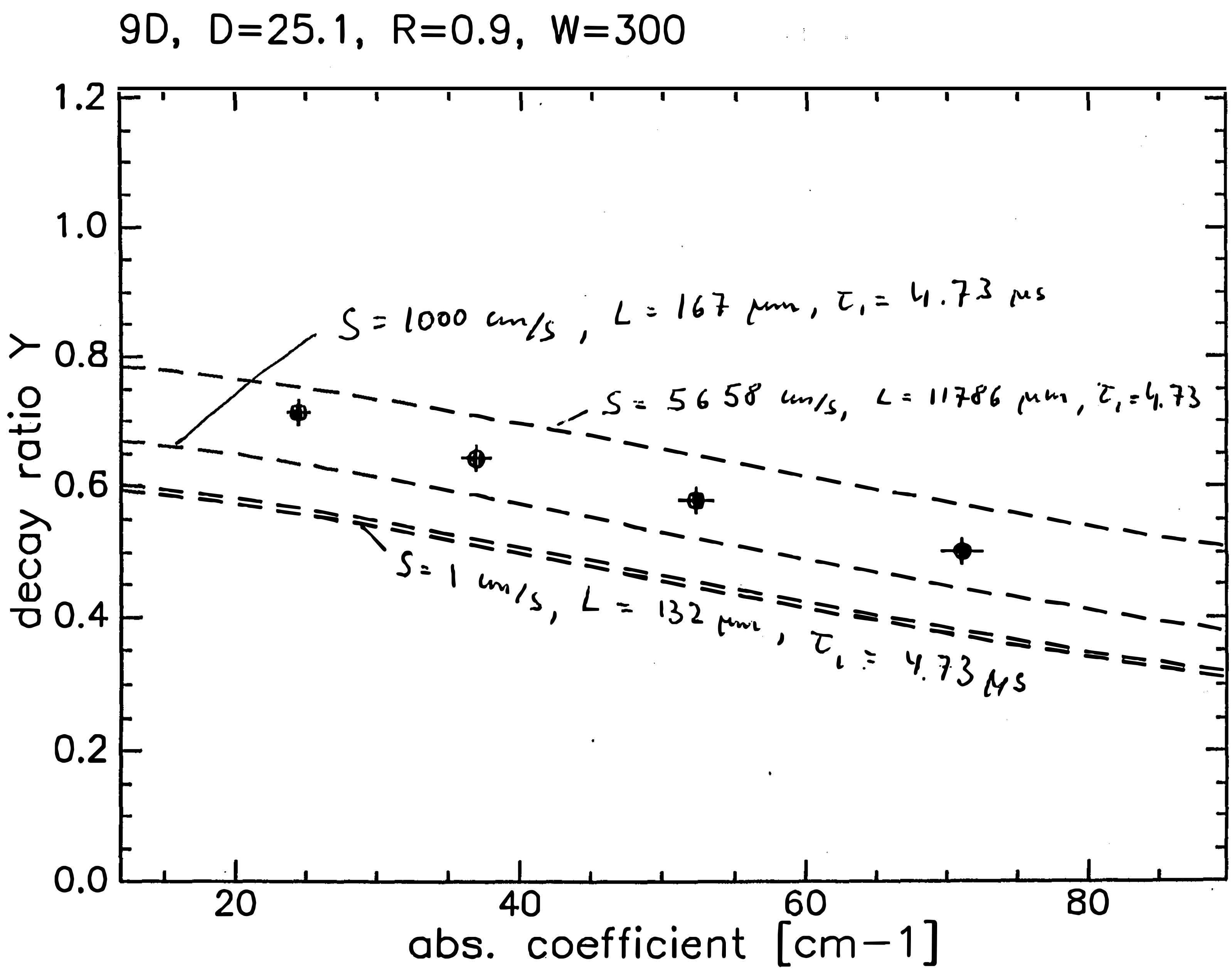

9D, D=25.1, R=0.9, W=300
decay ratio Y
abs. coefficient [cm−1]
S = 1000 cm/s, L = 167 μm, τ1 = 4.73 μs
S = 5658 cm/s, L = 11786 μm, τ1 = 4.73
S = 1 cm/s, L = 132 μm, τ1 = 4.73 μs

Fig. 6