Original and Supplementary Data for Paper:

“Bipolar device fabrication using a scanning tunneling microscope”

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Fig.1 - Original and supplementary STM images

STM Image processing:

- STM images were accquired with the Omicron Scala software using a unix control computer. Later (images in Figs. 4 and 5) we used a custom built in-house control software and hardware to accquire STM scans.
- The Gwyddion software package and pyplot was used to plot STM images
- Most Images were processed by subtracting a linear background
- In a few cases a line-by-line average subtraction was made
- For the figures in the paper the images were cropped, in some cases corrected for drift and scaled using the period of the dimer rows of the silicon (100) surface.

Fig. 1

Fig. 1b

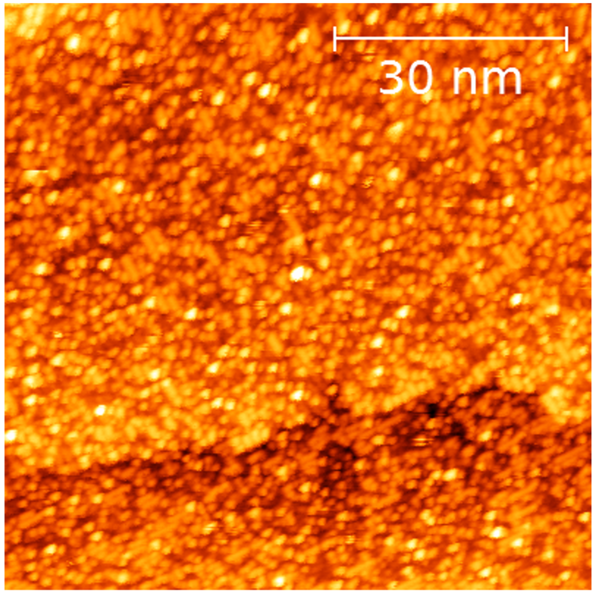


Fig. 1c

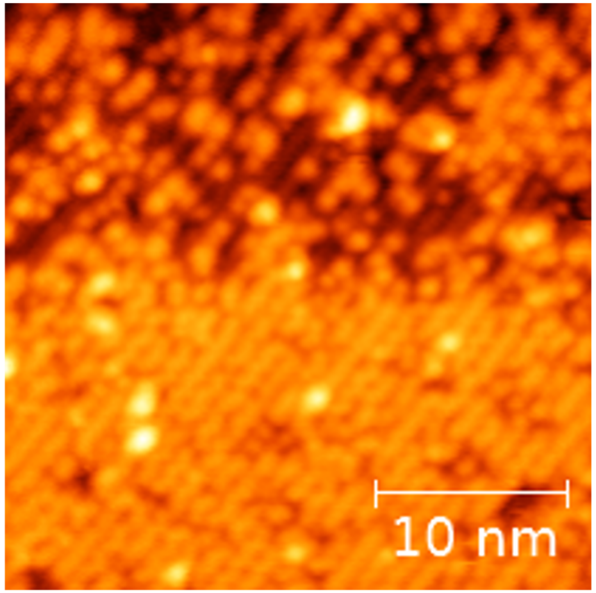


Fig. 1e

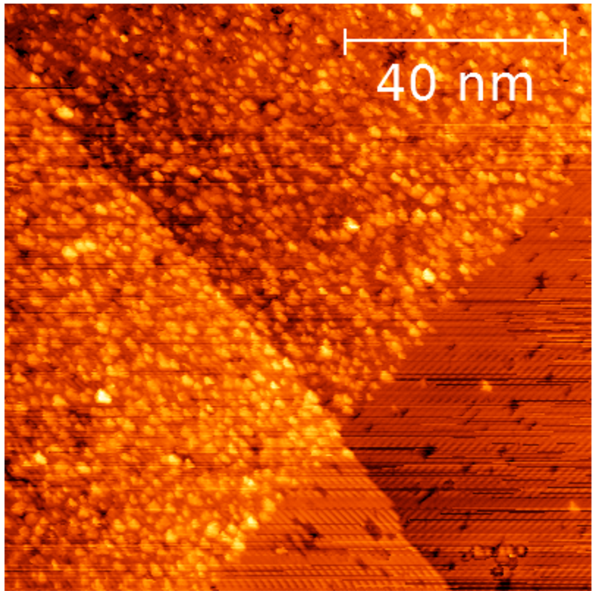


Fig. 1d

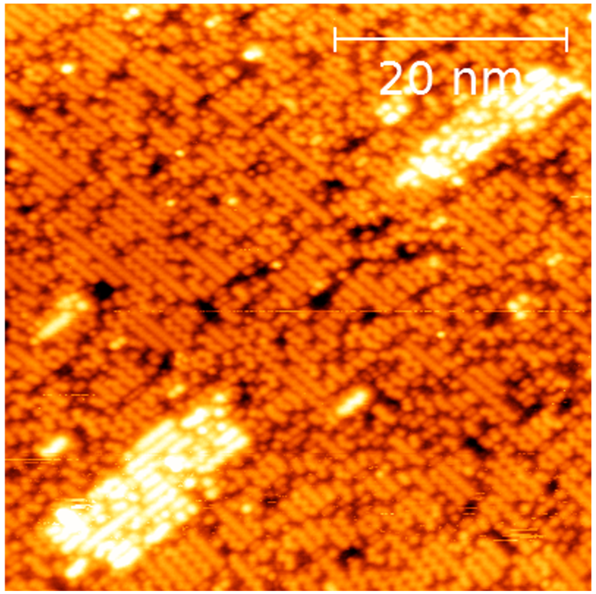
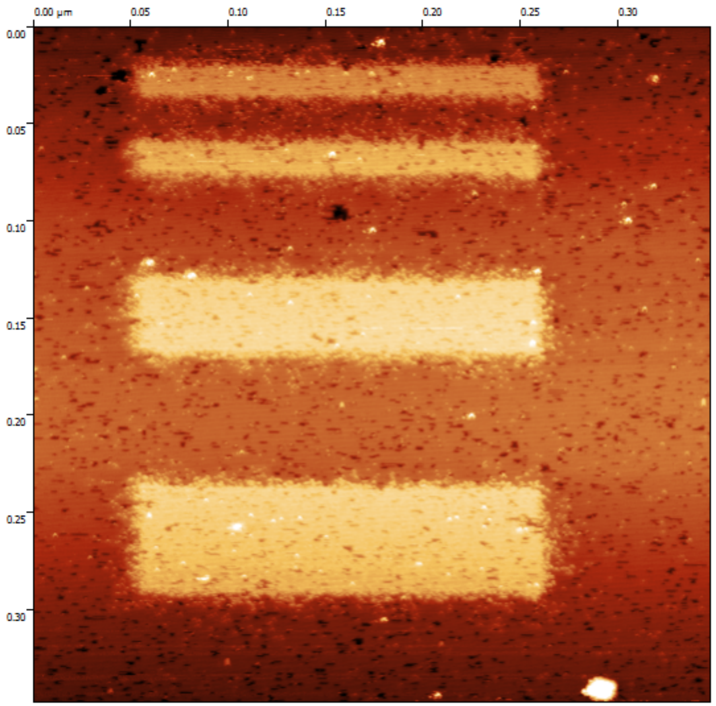
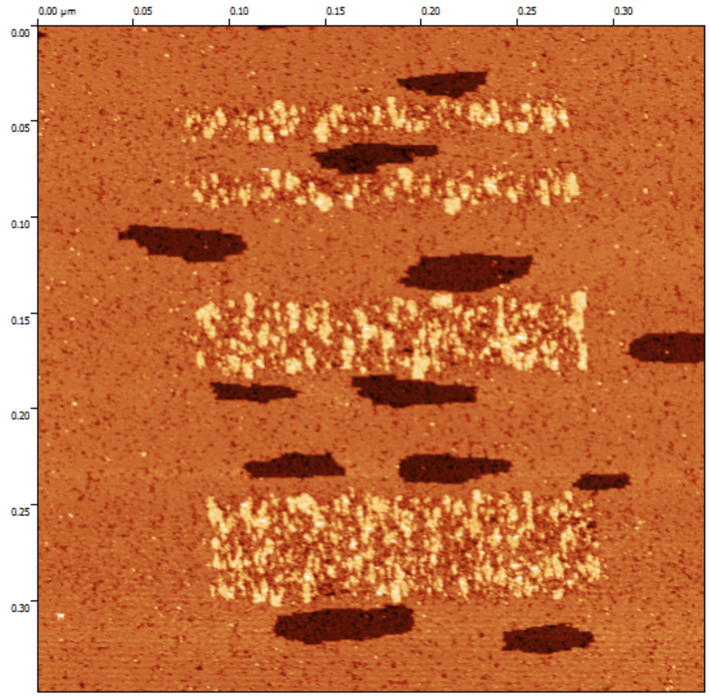


Fig. 1

Fig. 1f and g





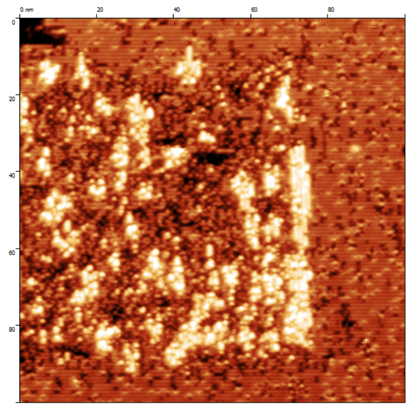
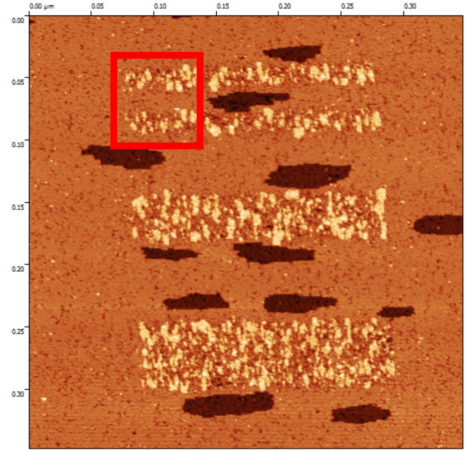
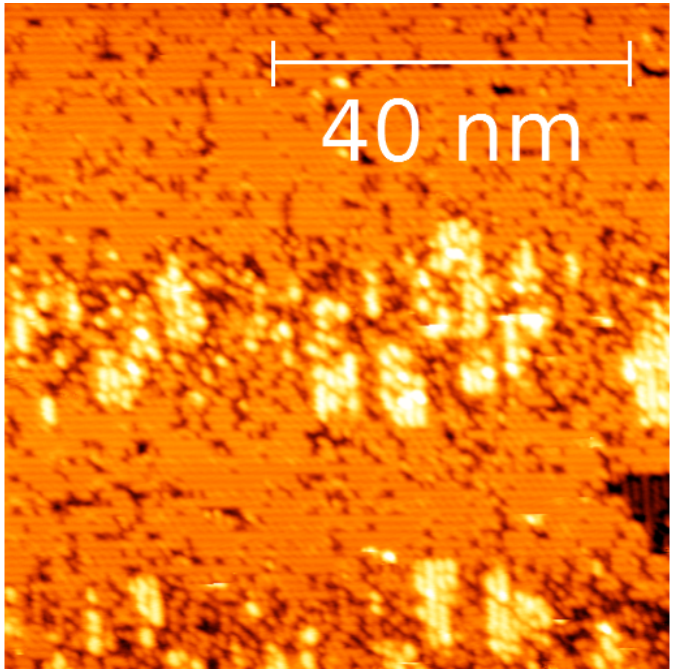


Fig. 1

Fig. 1f and g

zoom of upper region for Fig. 1g





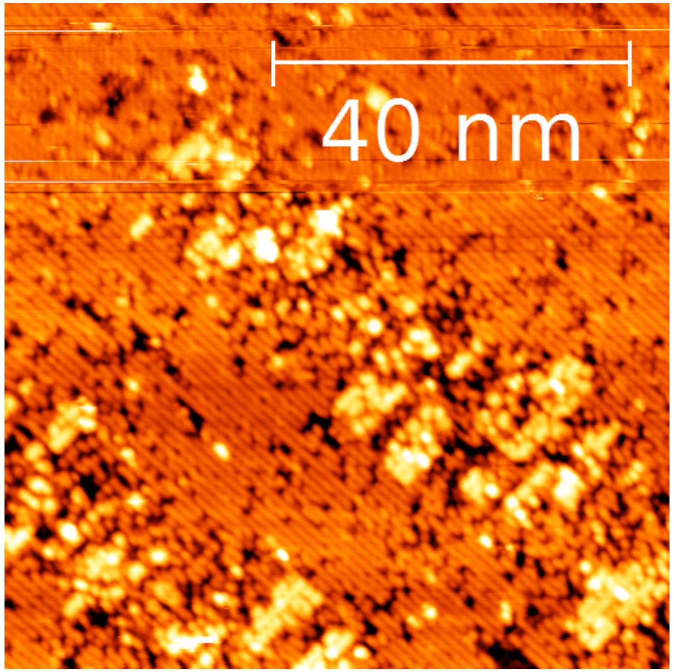


Fig. 1

Fig. 1f and g – additional data (not shown in paper)

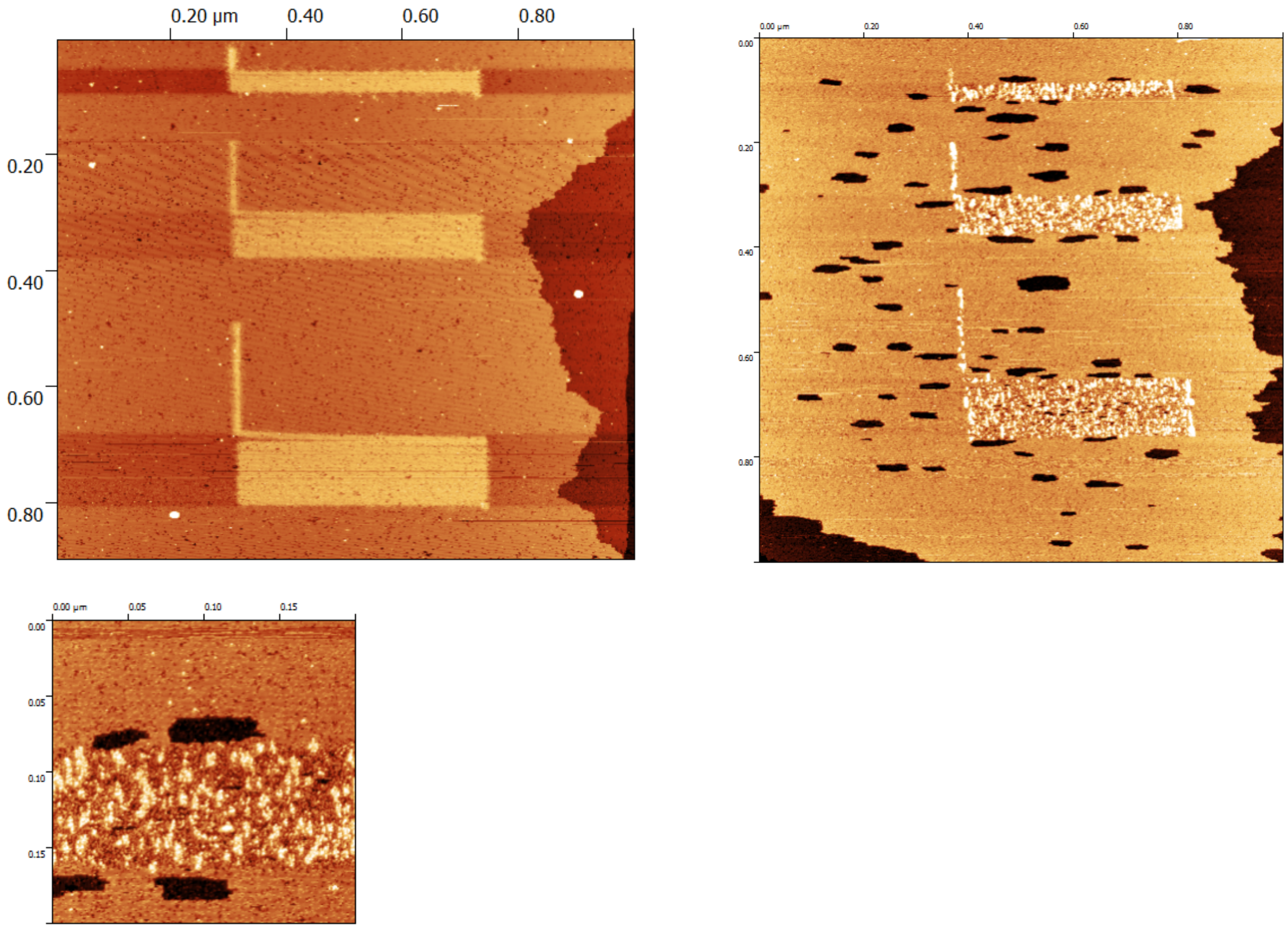
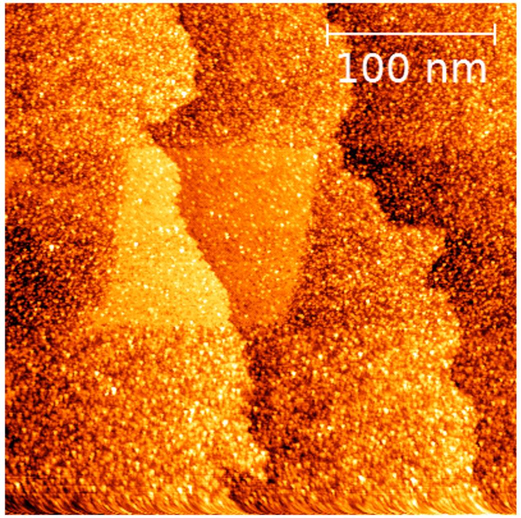


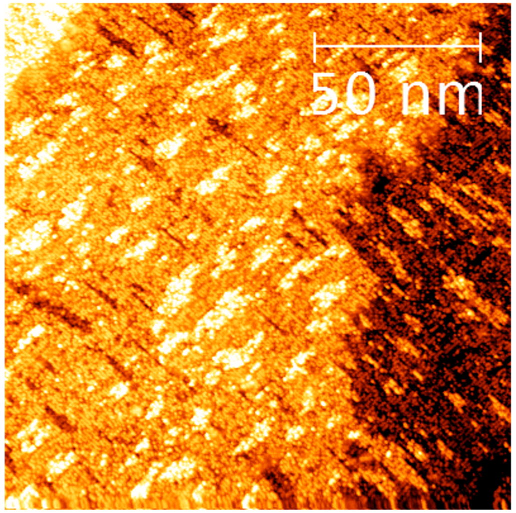
Fig. 1

Additional data (not shown in paper):
9L diborane dose and different in-situ anneals

350C 5min



350C 5min + 450C 5min



350C 5min + 450C 5min+
600C 2.5min+ 800 0.5min

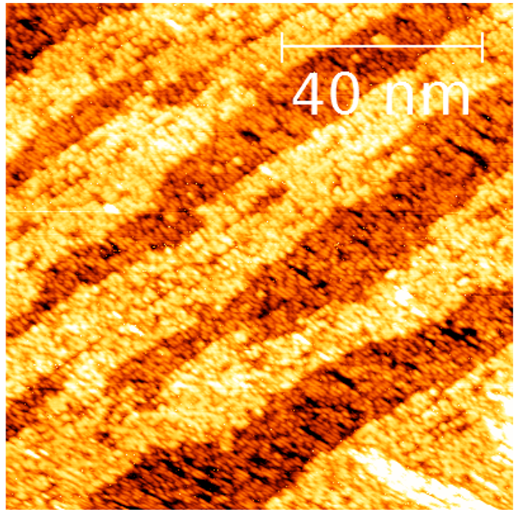
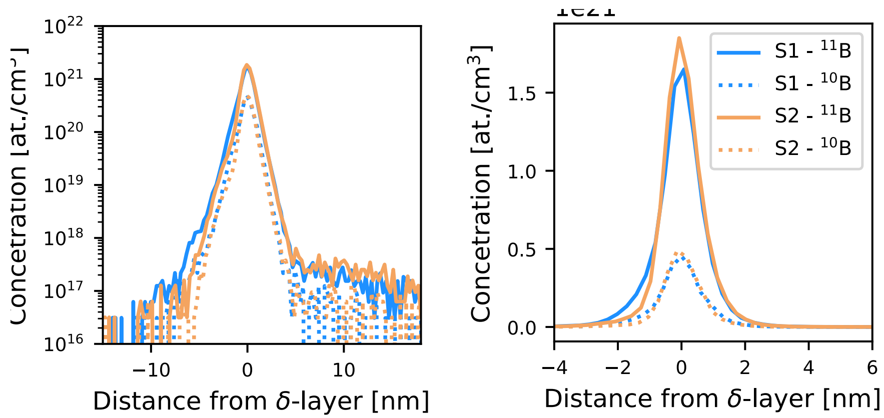


Fig. 2

SIMS data for:

- phosphorus δ-layer
- boron δ-layer
- boron with locking δ-layer



Comments & Info.csv
Data_BinSi Ref.csv
Data_PinSi_Ref.csv
Data_S1_InROI.csv
Data_S1_NextToROI.csv
Data_S2_InROI.csv
Data_S2_NextToROI.csv
Data_S3_NextToROI.csv
Data_S3_P-template_InROI.csv
Data_S3_P-template_NextToROI.csv
Depths.csv

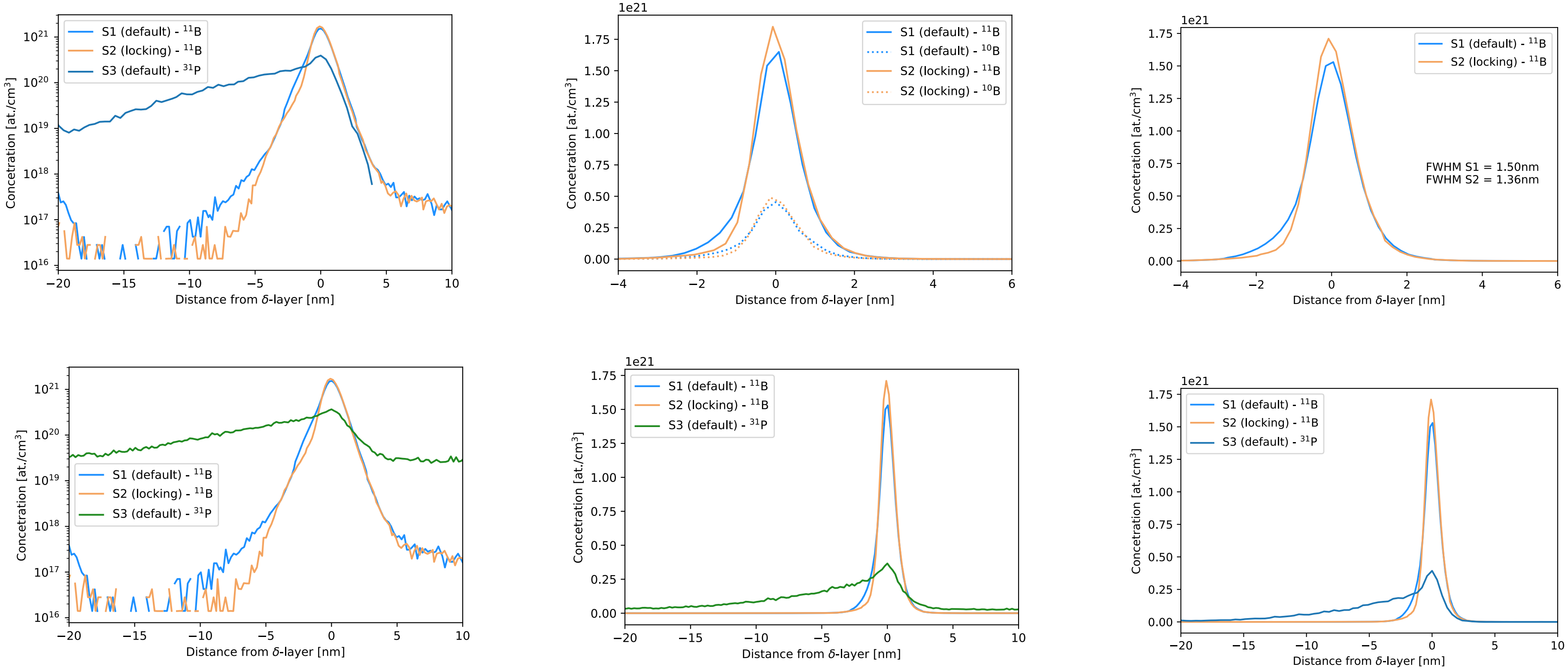


Fig.3 - Transport Data on boron δ-layers

Hall bar samples:

- typical sample size is 2.7 mm x 9 mm of which only a length of 5 - 6 mm contains the δ-layer
- the Hall bars are patterned using e-beam lithography and then cut into three chips which were annealed at different temperatures (sometimes sequentially after measurement)
- chips are glued into ceramic chip carriers with silver epoxy (epotec) and bonded using Al bond wire
- Rxx and Rxy was measured in two different cryostats (PPMS, Oxford Spectromag) for many Hall bars and standard Hall analysis was used to determine mobilities and densities

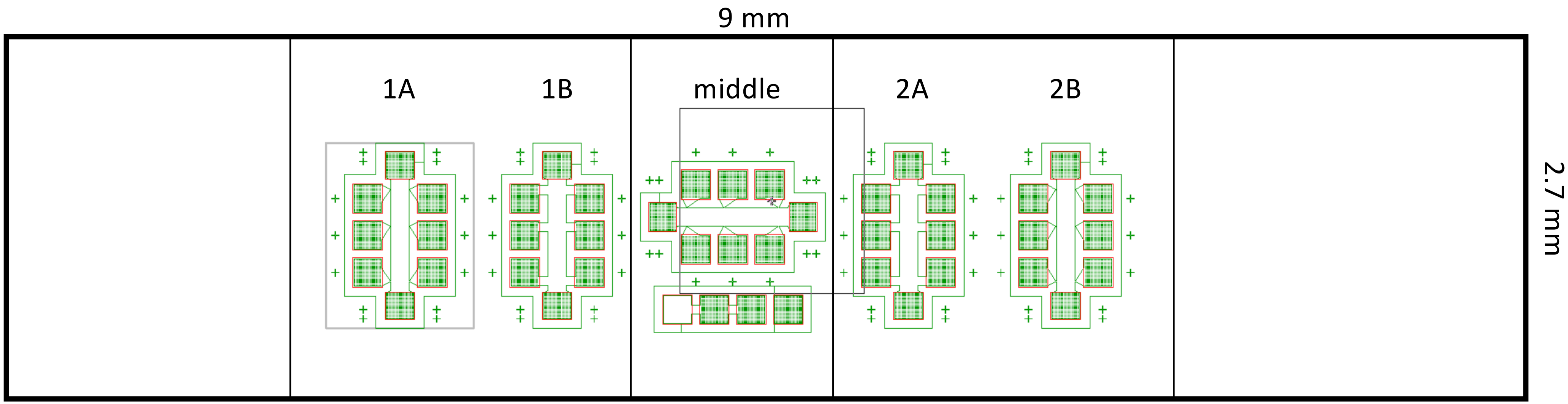


Fig. 3 - List of Samples

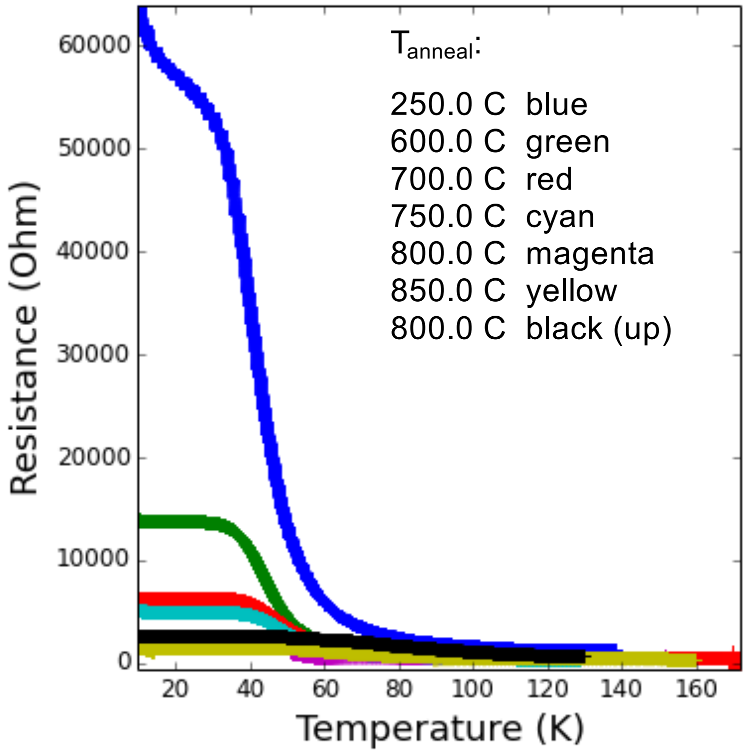
Sample name	***Symbol***	***part***	***type***	***Dose***	***Anneal T+time***	***Anneal type***	***Hallbar***	***Cryostat***	***Comments***	***Si overgrowth***
Notes				STM manipulator with resistive and ZUP	contact anneal not mentioned for any annealing procedure, in-situ Pyrometer if not otherwise stated	In-situ anneal in general with 1.5-2nm Si cap				standard, starting sample with resistive and start direct keeping it below 300C in Pyrometer
nSi#40		all	B delta	2.7L (slow open) 22%; 100-130C	350C Pyro 1min	In-situ	yes, Pt		first try of B delta	pyro below 300C
A					250C 2min contact anneal	Ex-situ				
	☆	middle, bonded						Oxford	**no measure between**	
B		1A			410C 2min	Ex-situ				
C		2A			650C 2min	Ex-situ				
D		1B			850C 2min	Ex-situ				
		2B								
nSi#48	△		B delta	338L heating forgot to note, probably 30%		*Ex-situ*	yes, Pt		sample cut and annealed after hallbar	18nm, standard
		1A			250C 2min / 800C 10s			Oxford		
		1B, bonded			250C 2min / 800C 1.5s			Oxford		
B		middle, bonded			250C 2min / 600C 2min / 800C 4s / 850C			Oxford		
A		2A/B, bonded			250C 2min / 800C 2min			Oxford		
nSi#54	□	all	B delta	570L		*Ex-situ*	yes, Pt		sample cut and annealed after hallbar	18nm, standard, temperature the lowest as possible with direct. for for Grenoble as a backup
		1A			250C 2min / 700C 2min / 850C 2min			ppms		
A, C		1B , bonded			250C 2min / 700C 2min / 900C 2min			ppms		
B, D, F		middle			600C 2min / 750C 2min / 850C 80s			Ppms / Oxford	new contacts after	
E		2A / 2B			800C 2min			Ppms / Oxford	sample lost	
nSi#83	✕	all	B delta	900L, 30%	13s 850C Pyro	In-situ	yes Pt		temp possibly a bit lower, mainly watched current	15nm, start standard, after 2nm turn out sample, 850C 5sec (might have been even shorter difficult with power supply), continue growth 5min 350C,then
A		middle, bonded						Oxford		
		1A								
		1B (dirt)								
		2A								
		2B								
nSi#88	+	all	B delta	570L, 30%	10s, 830C 2.5A, last 2-3s corrected to 850C	In-situ	yes, Pt		2nm interlayer standard, then incorporation anneal	15nm standard
A		middle, bonded						Oxford		
		1A,1B, 2A,2B								
nSi#129	◊	all	B delta	90L,25% 95c-176C	1.5min 350C, 0.5min 405C	In situ	yes, Pt		no interlayer before in-situ anneal. ex-situ in RTA clean room	18nm standard
		all			contact anneal 250C 1.5min	Ex-situ				
		middle			1080C 2min					
		1A			850C 2min, 931C 2min	Ex-situ				
A		1B			410C 2min,?C 2min	Ex-situ				
B		2A			650C 2min	Ex-situ				
		2B			1000C 2min	Ex-situ			dirty	

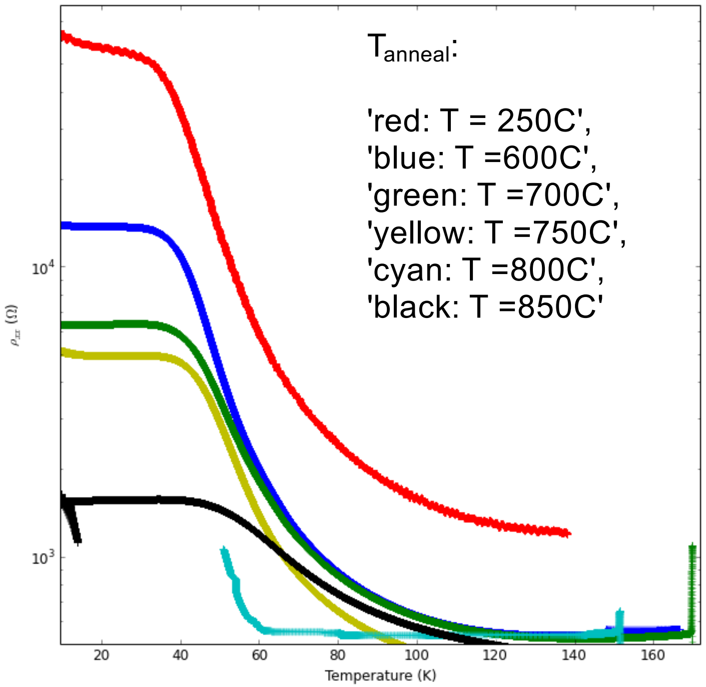
in-situ 250C 2min

Fig. 3a Temp-sweeps overview (PPMS)

nSi#54 590L dose

Sample nSi#54

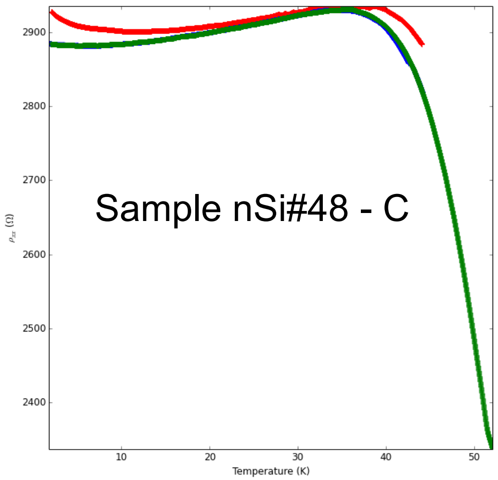




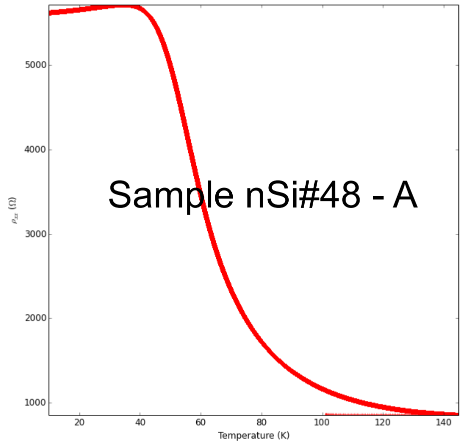
in-situ 250C 2min

Fig. 3a Temp-sweeps overview (Oxford)

nSi#48 338L dose



T sweep
Tanneal = 800C 4s



T sweep
Tanneal=800C 10s
less Diborane

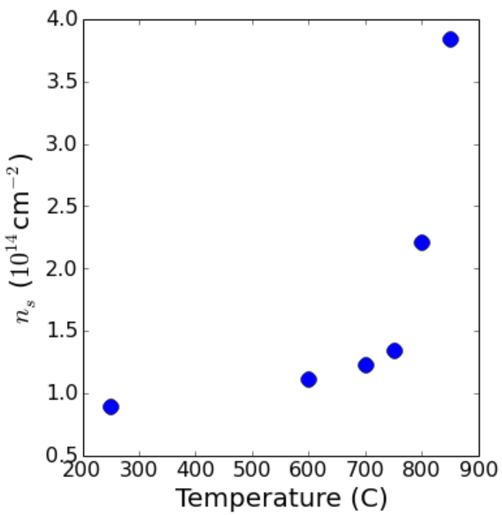
in-situ 250C 2min

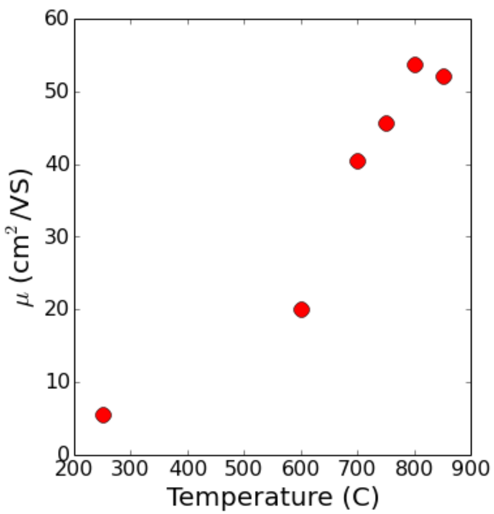
Fig. 3c-d Magnetoresistance Data nSi#54

nSi#54 590L dose

- Measured on PPMS system
- 900C sample had contact problems after anneal

Measurement Temperature T_M=10K





mobility and density as a function of annealing temperature extracted from the following Hall measurements

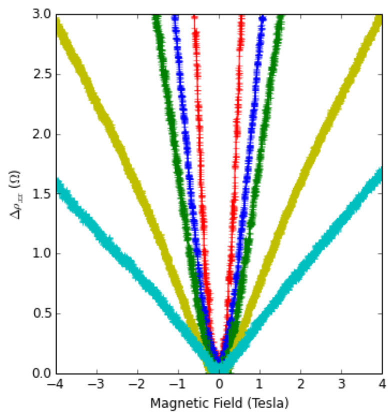
Sample nSi#54

in-situ 250C 2min

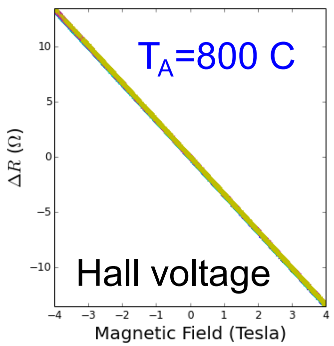
Fig. 3c-d Magnetoresistance Data nSi#54

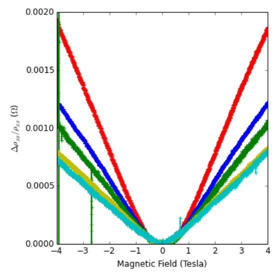
nSi#54 590L dose

Temperature T_M=15K

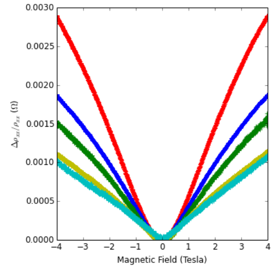


T_A :
red - 600 C
blue - 700 C
cyan - 850 C
green - 750 C
yellow - 800 C

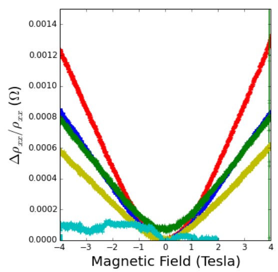




Temperature
T=10K



Temperature
T=15K



Temperature
T=20K

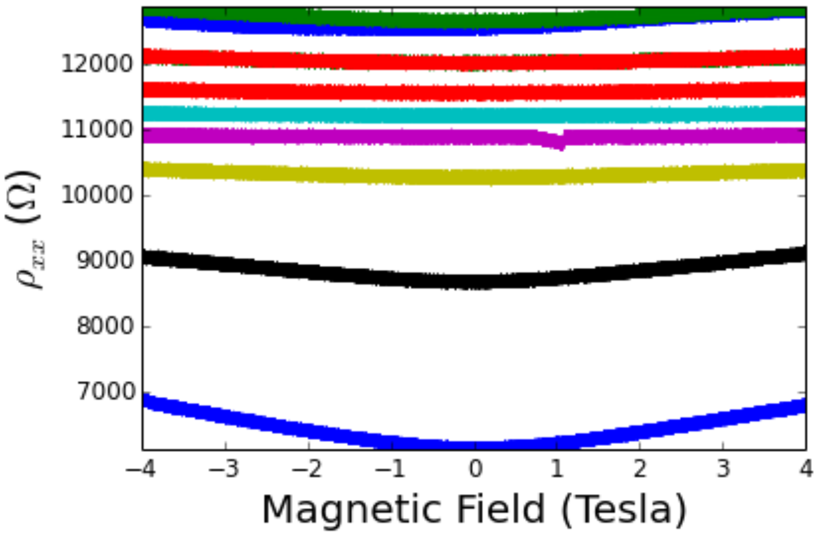
Sample nSi#54

in-situ 250C 2min

Fig. 3c-d B sweeps 250C sample (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	nan	0.9	5.54	12568.93	0.08
green	15	0.94	5.49	12039.13	0.083
red	20	0.98	5.51	11578.03	0.086
cyan	25	1	5.54	11231.01	0.089
magenta	30	1.04	5.51	10913.3	0.092
yellow	35	1.05	5.79	10282.22	0.097



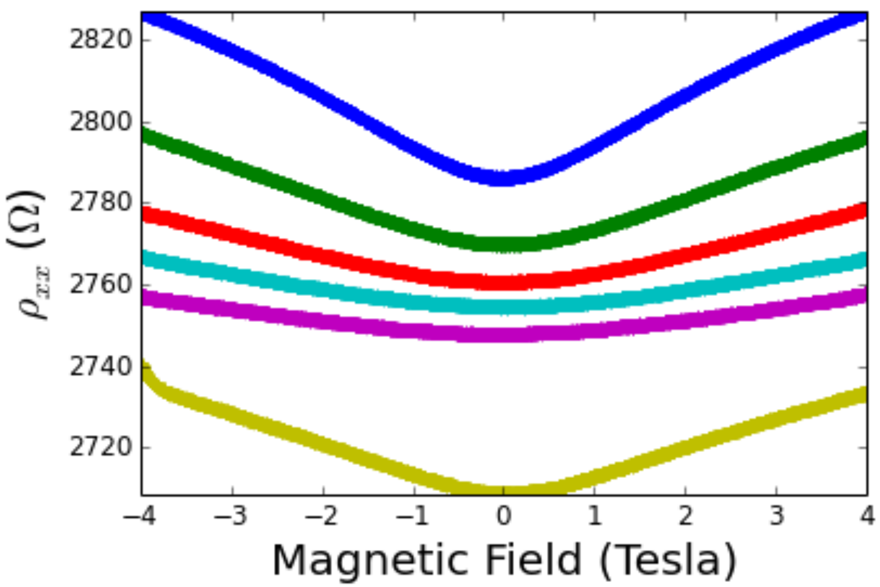
Sample nSi#54

in-situ 250C 2min

Fig. 3c-d B sweeps 600 C sample (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0 (mS)
blue	10	1.12	20.06	2786.1	0.359
green	15	1.14	19.72	2769.85	0.361
red	20	1.16	19.51	2760.54	0.362
cyan	25	1.17	19.35	2754.51	0.363
magenta	30	1.18	19.27	2747.69	0.364
yellow	35	1.18	19.46	2708.75	0.369



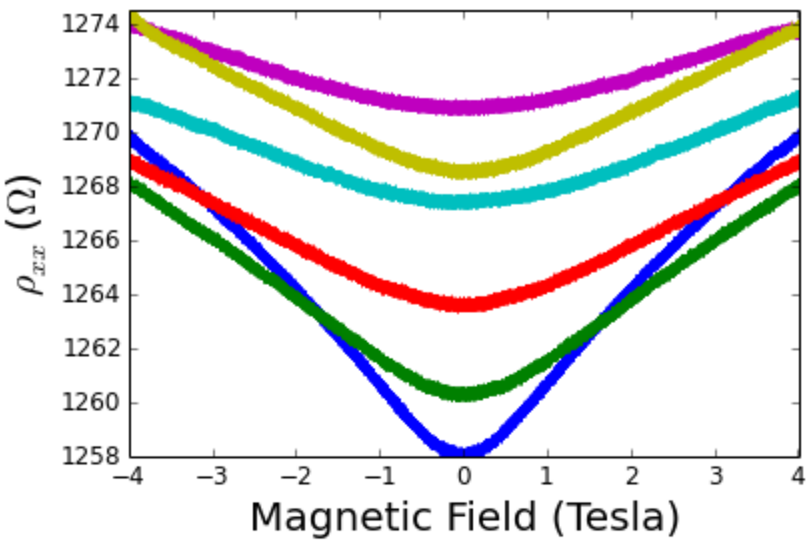
Sample nSi#54

in-situ 250C 2min

Fig. 3c-d B sweeps 700 C sample (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	10	1.23	40.46	1258.1	0.795
green	15	1.24	39.96	1260.34	0.793
red	20	1.25	39.57	1263.65	0.791
cyan	25	1.26	39.21	1267.46	0.789
magenta	30	1.26	38.92	1270.95	0.787
yellow	35	1.27	38.89	1268.58	0.788



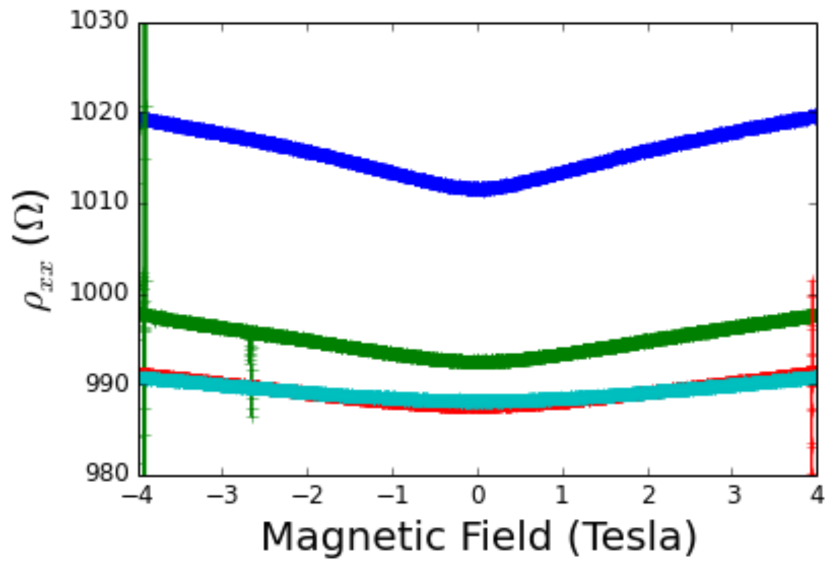
Sample nSi#54

in-situ 250C 2min

Fig. 3c-d B sweeps 750 C sample (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	10	1.35	45.74	1011.62	0.989
green	15	1.39	45.37	992.54	1.008
red	20	1.41	44.71	987.64	1.013
cyan	25	1.42	44.53	988.16	1.012



Sample nSi#54

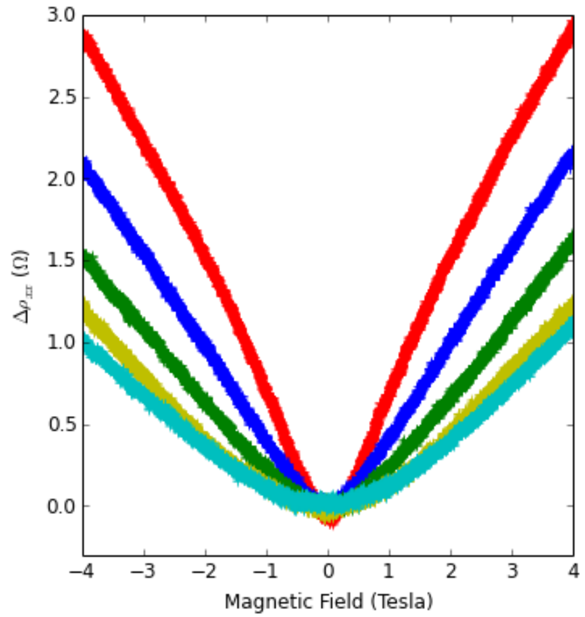
in-situ 250C 2min

Fig. 3c-d B sweeps 800C sample (Oxford)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0 (mS)
blue	4	2.15	56.34	516.05	1.938
green	6	2.18	54.81	521.95	1.916
red	8.7	2.27	52.67	522.05	1.916
cyan	10.8	2.4	49.75	522.27	1.915
magenta	4	2.22	54.1	520.88	1.92
yellow	6	2.21	54.21	521.97	1.916

blue - 15.0
cyan - 30.0
green - 20.0
yellow - 25.0
red - 10.0



Sample nSi#54

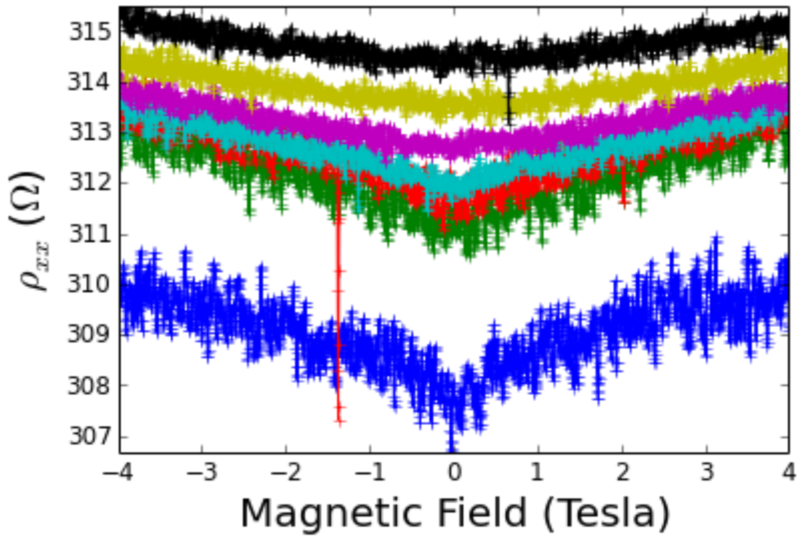
in-situ 250C 2min

Fig. 3c-d   B sweeps 850C sample (Oxford)

Measurement Temperature dependence

T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
4.6	2.17	93.65	307.72	3.25
6.8	3.21	62.41	311.17	3.214
8.8	3.4	58.92	311.71	3.208
10.9	3.38	59.15	311.96	3.206
16.1	3.62	55.21	312.74	3.198
21.2	3.57	55.76	313.56	3.189
25.9	3.52	56.46	314.46	3.18
4.6	-2.35	86.24	307.87	3.248
6.7	3.43	58.51	311.16	3.214
8.8	3.2	62.51	311.77	3.207
10.9	3.57	56.04	312.02	3.205
15.7	3.26	61.29	312.65	3.198
20.3	3.25	61.23	313.45	3.19
24.7	3.4	58.49	314.28	3.182

4.6 K - blue
6.8 K - green
8.8 K - red
10.9 K - cyan
16.1 K – magenta
21.2 K - yellow
25.9 K - black



Sample nSi#54

in-situ 250C 2min

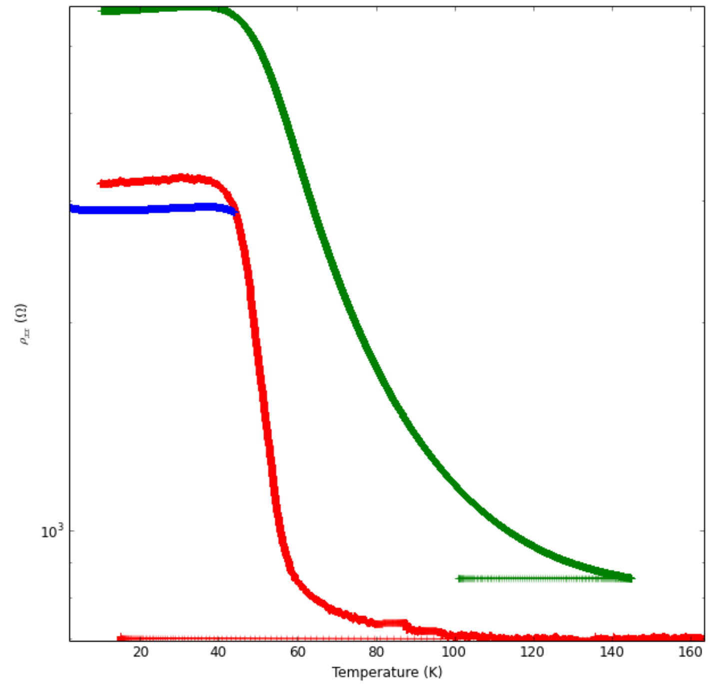
Fig. 3c-d Sample nSi#48

Annealing time dependence at 800C:

- At least for 10s still seems metallic down to 10K
- Densities for 4s better than for others! But close to 120s, 10s about 2x smaller
- For 4sec at low T resistance rising again? (others not measured for such small T)

T_{anneal} :

red = 2min
blue= 4sec
green=10sec

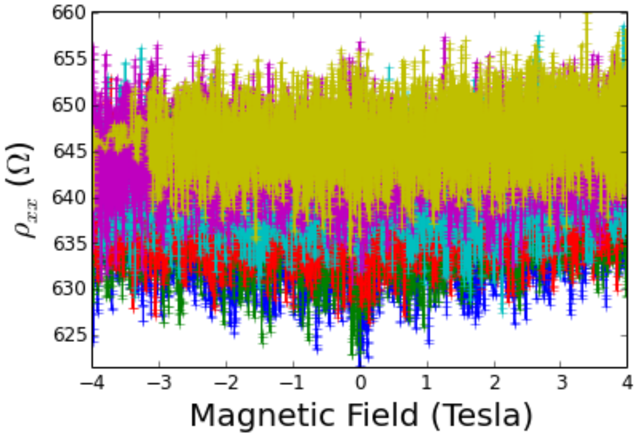


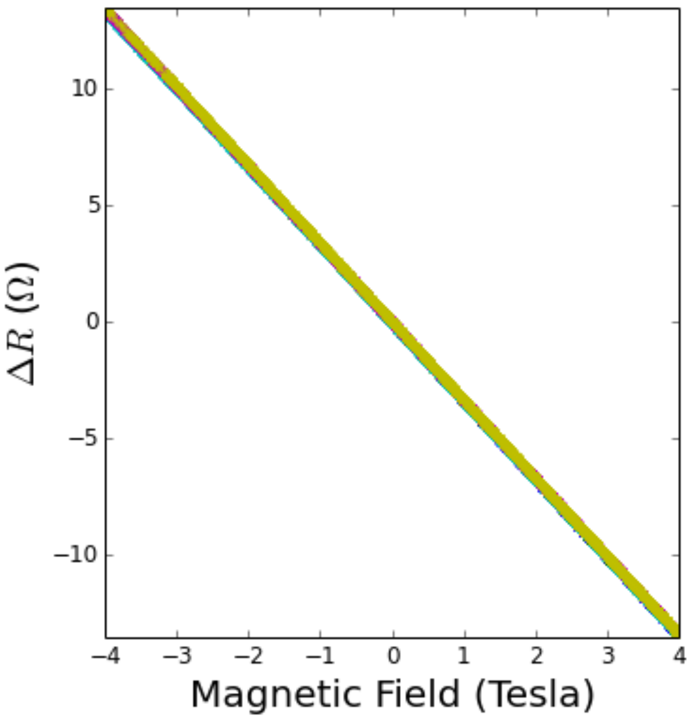
in-situ 250C 2min

Fig. 3c-d B sweeps 800C 120s (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0 (mS)
blue	10	-1.86	52.76	635.17	1.574
green	15	-1.87	52.51	635.86	1.573
red	20	-1.87	52.24	638.25	1.567
cyan	25	-1.87	51.99	641.45	1.559
magenta	30	-1.87	51.82	644.02	1.553
yellow	35	-1.87	51.81	645.93	1.548





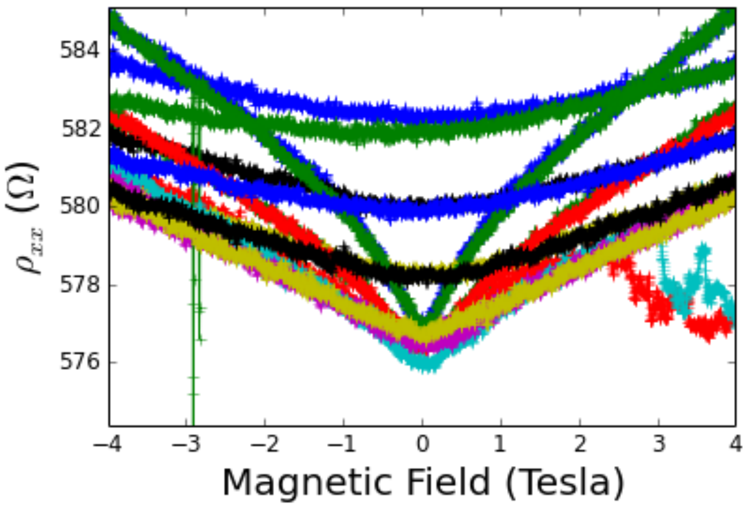
Sample nSi#48

in-situ 250C 2min

Fig. 3c-d   B sweeps 800C 4s (Oxford)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0 (mS)
blue	2.6	2.07	52.25	576.96	1.733
green	4.6	2.09	51.89	576.48	1.735
red	6.6	2.1	51.65	576.49	1.735
cyan	8.7	2.1	51.5	576.46	1.735
magenta	10.8	2.11	51.34	576.88	1.733
yellow	16.1	2.11	51.04	578.28	1.729
black	21	2.12	50.83	580.02	1.724
blue	25.7	2.12	50.63	582.29	1.717
green	2.7	2.07	52.22	576.99	1.733
red	4.6	2.09	51.86	576.48	1.735
cyan	6.6	2.1	51.69	575.98	1.736
magenta	8.6	2.1	51.5	576.45	1.735
yellow	10.7	2.11	51.34	576.76	1.734
black	15.7	2.11	51.05	578.26	1.729
blue	20.2	2.12	50.85	579.89	1.724
green	24.6	2.12	50.63	582.31	1.717



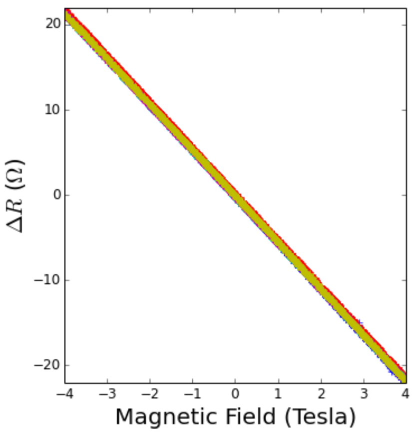
Sample nSi#48

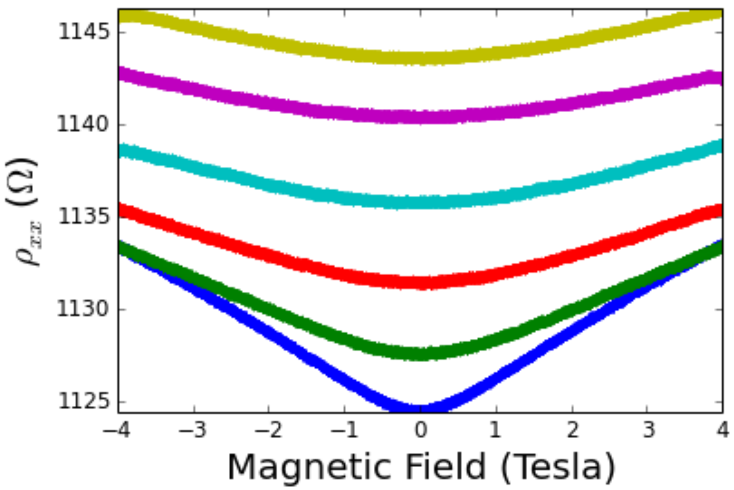
in-situ 250C 2min

Fig. 3c-d B sweeps 800C 10s (PPMS)

Temperature dependence

	T(K)	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	10	1.15	48.34	1124.53	0.889
green	15	1.16	47.91	1127.62	0.887
red	20	1.16	47.58	1131.47	0.884
cyan	25	1.16	47.27	1135.82	0.88
magenta	30	1.16	47.11	1140.43	0.877
yellow	35	1.16	47.15	1143.61	0.874



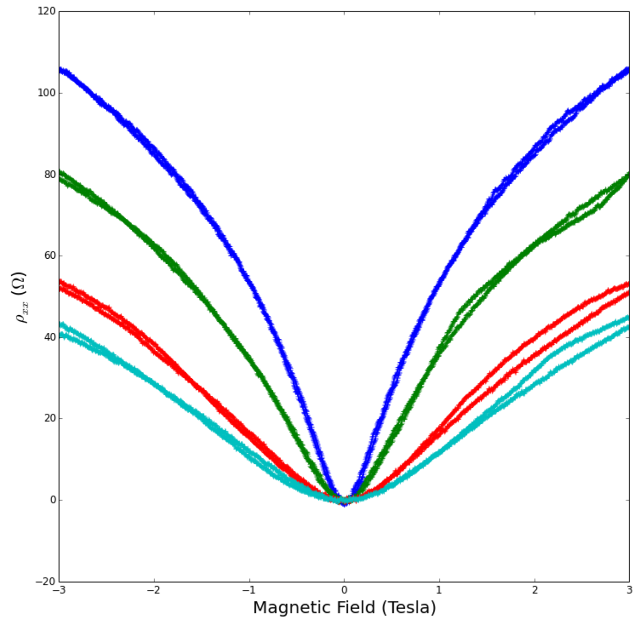


Sample nSi#48

Fig. 3c-d Nsi#40 410C 2min

in-situ 350C 1min

	T(K)	[Tdiff]	Ns(nm-2)	Mu(cm2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.5	0.1	1.08	20.24	2855.5	0.35
blue	2.5	0.1	1.08	20.24	2856.14	0.35
green	4.5	0.26	1.13	19.7	2813.95	0.355
green	4.6	0.25	1.13	19.69	2812.57	0.356
red	9.3	0.68	1.18	19.15	2771.82	0.361
red	8.9	0.6	1.17	19.18	2773.65	0.361
cyan	11.8	0.92	1.19	18.98	2759.36	0.362
cyan	11.2	0.79	1.19	19.02	2762.26	0.362

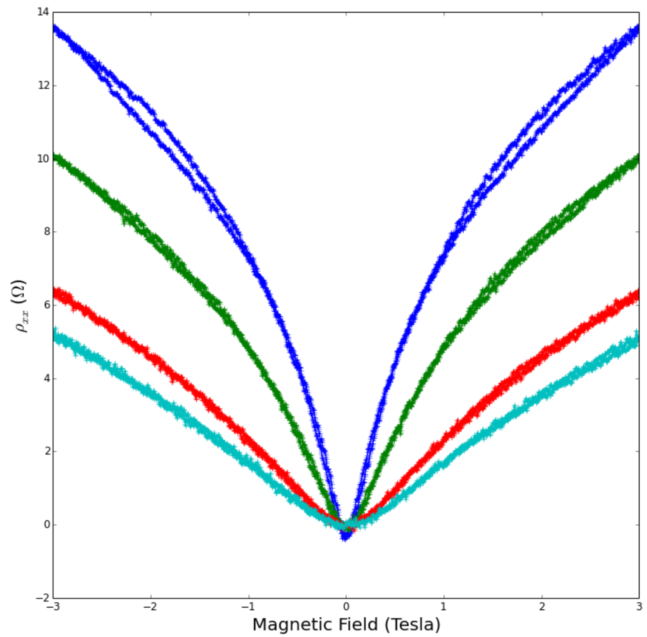


Sample nSi#40

Fig. 3c-d Nsi#40 850C 2min

in-situ 350C 1min

	T(K)	T_{diff}	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.4	0.2	1.3	57.95	829.07	1.206
blue	2.4	0.2	1.31	57.6	829.08	1.206
green	4.6	0.23	1.32	57.07	827.49	1.208
green	4.6	0.22	1.32	57.01	827.48	1.208
red	9	0.57	1.34	56.49	827.53	1.208
red	8.9	0.42	1.34	56.41	827.48	1.208
cyan	11.5	0.88	1.34	56.37	828.11	1.208
cyan	11	0.41	1.34	56.21	828.02	1.208

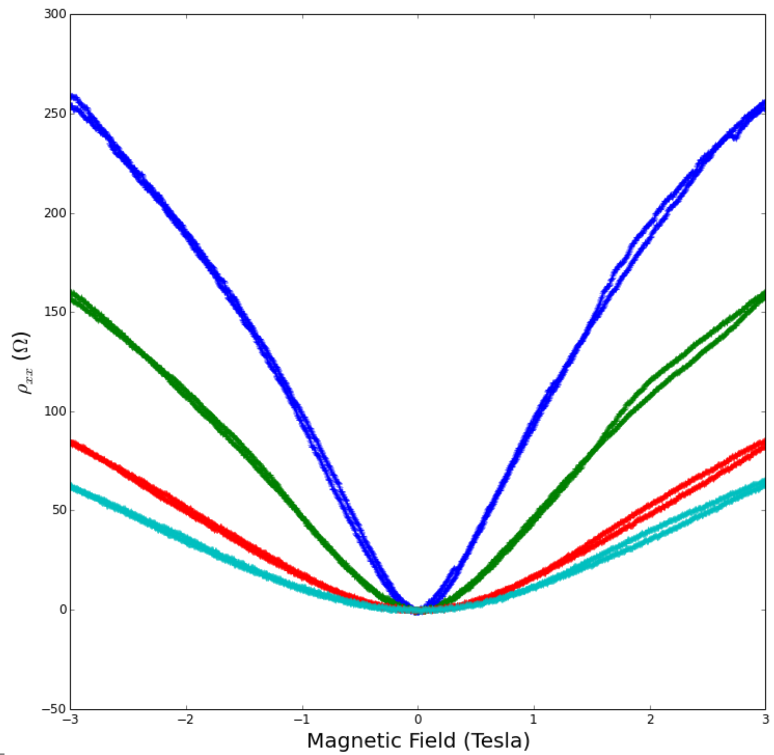


Sample nSi#40

1.5min 350C + 0.5min 405C

Fig. 3c-d Nsi#129 410C 2min ex-situ

	T(K)	[Tdiff]	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.4	0.1	0.9	15.08	4602.88	0.217
blue	2.4	0.13	0.9	15.09	4599.48	0.217
green	4.5	0.12	0.97	14.3	4522.29	0.221
green	4.6	0.2	0.96	14.32	4520.52	0.221
red	8.8	0.25	1.03	13.68	4442.44	0.225
red	8.8	0.32	1.03	13.7	4442.55	0.225
cyan	11.3	0.4	1.05	13.47	4415.12	0.226

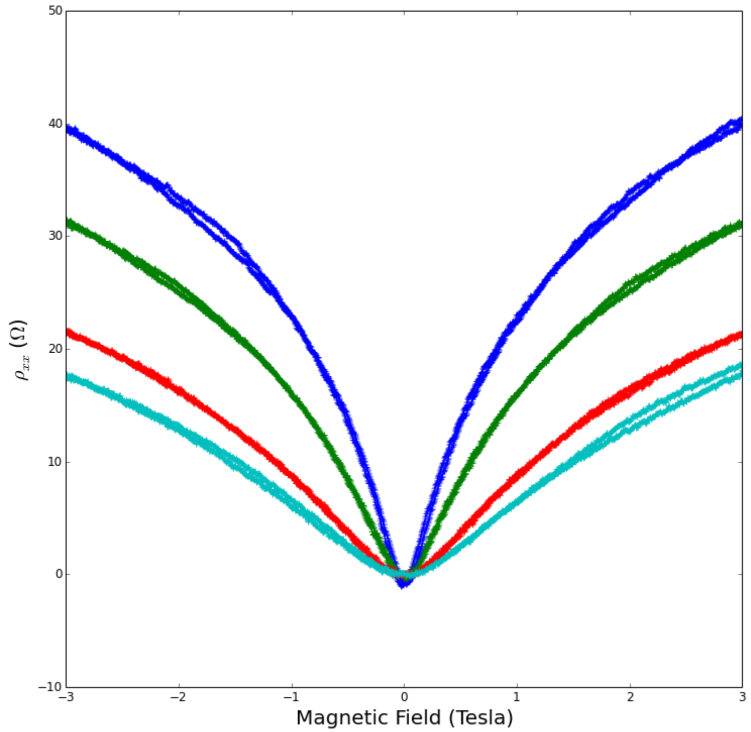


Sample nSi#129

Fig. 3c-d   Nsi#40 650C 2min

in-situ 350C 1min

	T(K)	[Tdiff]	Ns(nm-2)	Mu(cm2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.3	0.1	1.18	34.89	1510.31	0.662
blue	2.4	0.1	1.18	34.89	1510.25	0.662
green	4.5	0.12	1.21	34.3	1499.08	0.667
green	4.5	0.16	1.21	34.3	1499.03	0.667
red	8.9	0.26	1.24	33.69	1489.42	0.671
red	8.9	0.26	1.24	33.7	1489.41	0.671
cyan	11.5	0.58	1.25	33.47	1486.61	0.673
cyan	11.1	0.61	1.25	33.51	1486.89	0.673

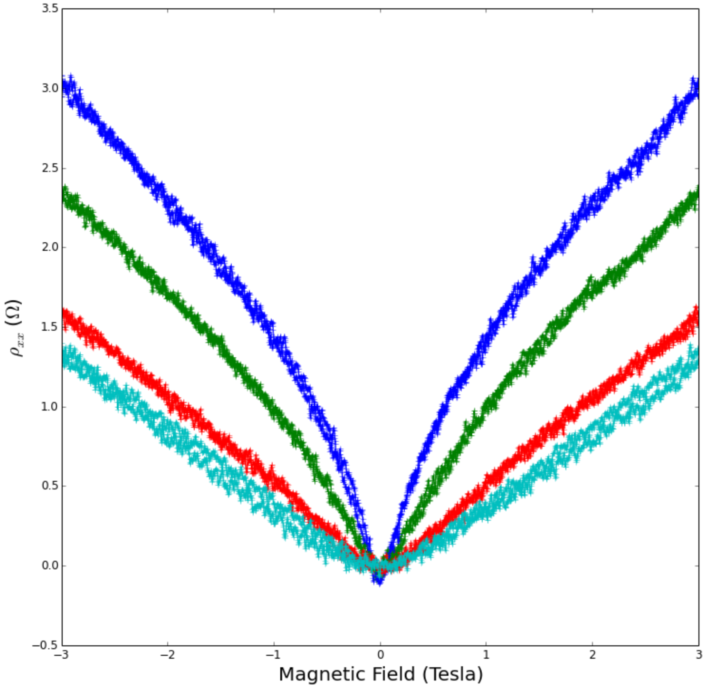


Sample nSi#40

1.5min 350C + 0.5min 405C

Fig. 3c-d Nsi#129 850C 2min

	T(K)	[Tdiff]	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.3	0.06	3.23	55.61	347.79	2.875
blue	2.3	0.06	3.24	55.46	347.78	2.875
green	4.4	0.05	3.25	55.28	347.42	2.878
green	4.5	0.29	3.3	54.38	347.4	2.879
red	8.8	0.23	3.31	54.31	347.27	2.88
red	8.7	0.28	3.26	55.13	347.25	2.88
cyan	11.3	0.98	3.3	54.36	347.41	2.878
cyan	10.8	0.51	3.27	55.02	347.34	2.879

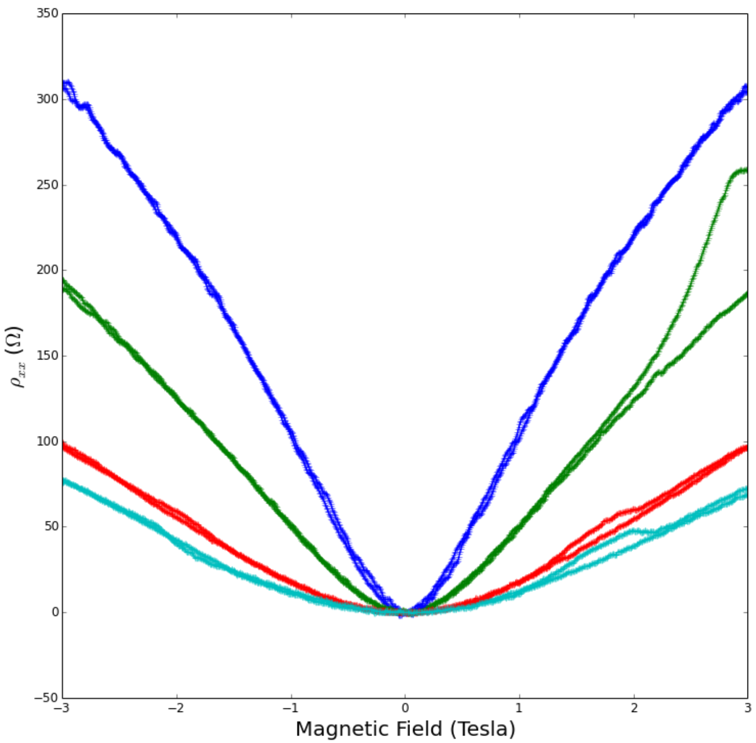


Sample nSi#129

1.5min 350C + 0.5min 405C

Fig. 3c-d Nsi#129 in-situ

	T(K)	[Tdiff]	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.5	0.06	0.85	13.42	5500.54	0.182
blue	2.5	0.09	0.84	13.43	5502.46	0.182
green	4.4	0.89	0.9	12.88	5388.98	0.186
green	4.5	0.1	0.91	12.78	5387.05	0.186
red	8.9	0.23	0.98	12.13	5270.01	0.19

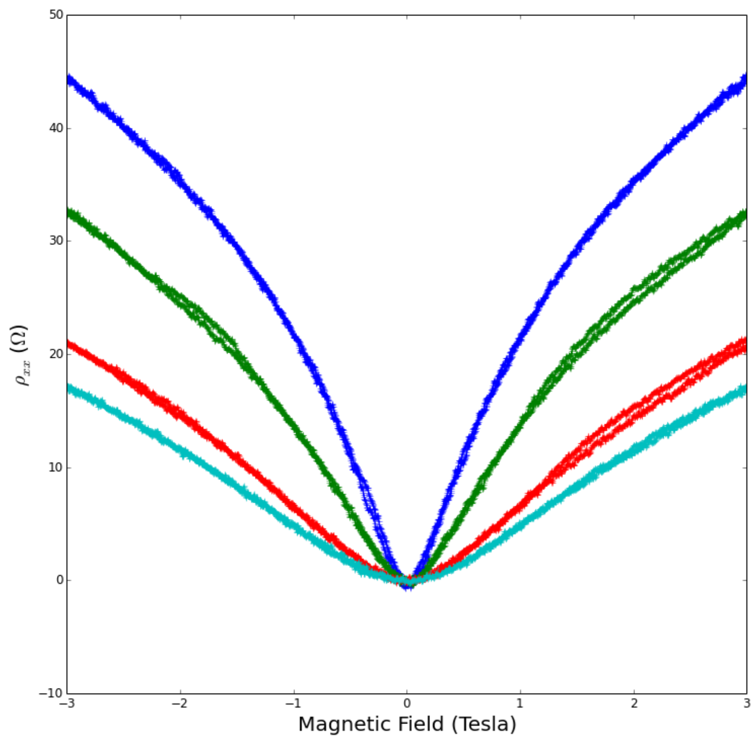


Sample nSi#129

1.5min 350C + 0.5min 405C

Fig. 3c-d Nsi#129 650C 2min

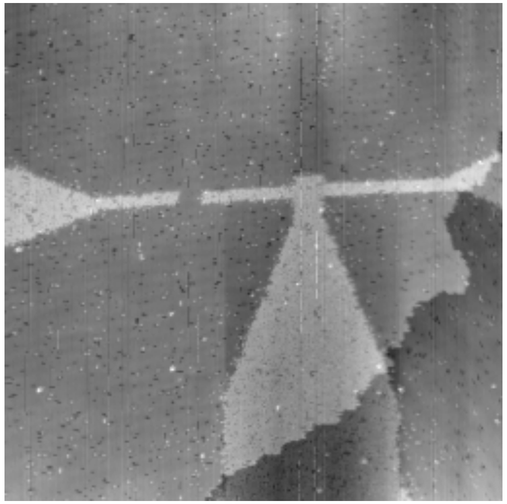
	T(K)	[Tdiff]	Ns(nm^{-2})	Mu(cm^2/Vs)	Rho0(Ohm)	Sig0(mS)
blue	2.4	0.08	1.11	33.05	1703.84	0.587
blue	2.3	0.06	1.11	33.03	1704.06	0.587
green	4.5	0.17	1.14	32.34	1692.09	0.591
green	4.5	0.22	1.14	32.35	1691.79	0.591
red	8.9	0.31	1.17	31.69	1682.47	0.594
red	8.7	0.42	1.17	31.71	1682.7	0.594



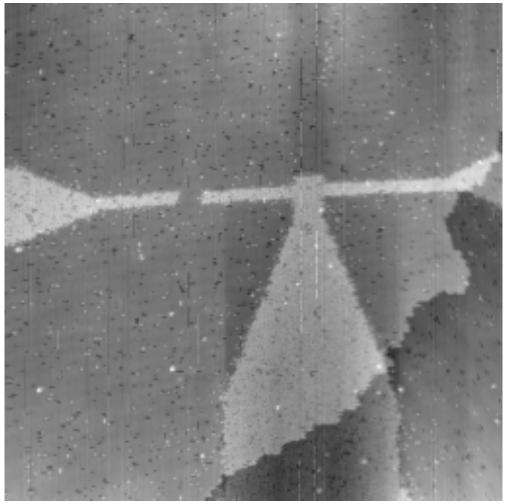
Sample nSi#129

Fig. 4

raw STM images of device



A160620.144723.dat



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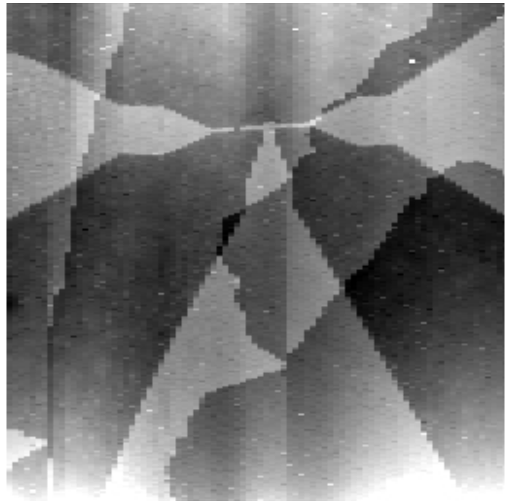

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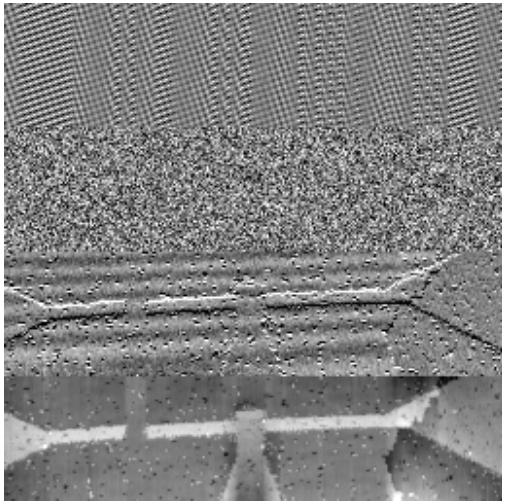

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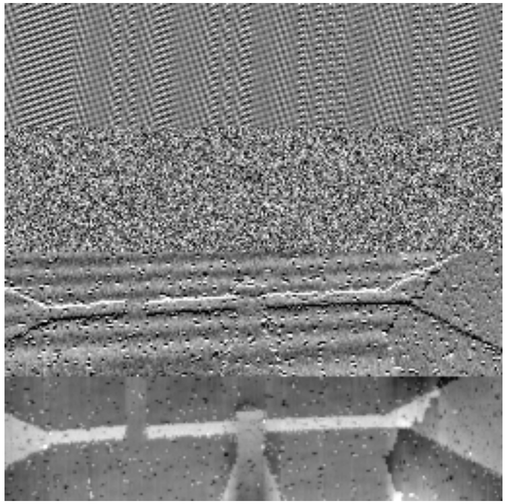

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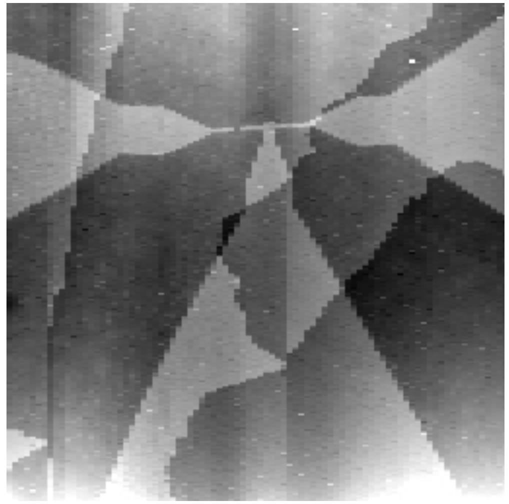
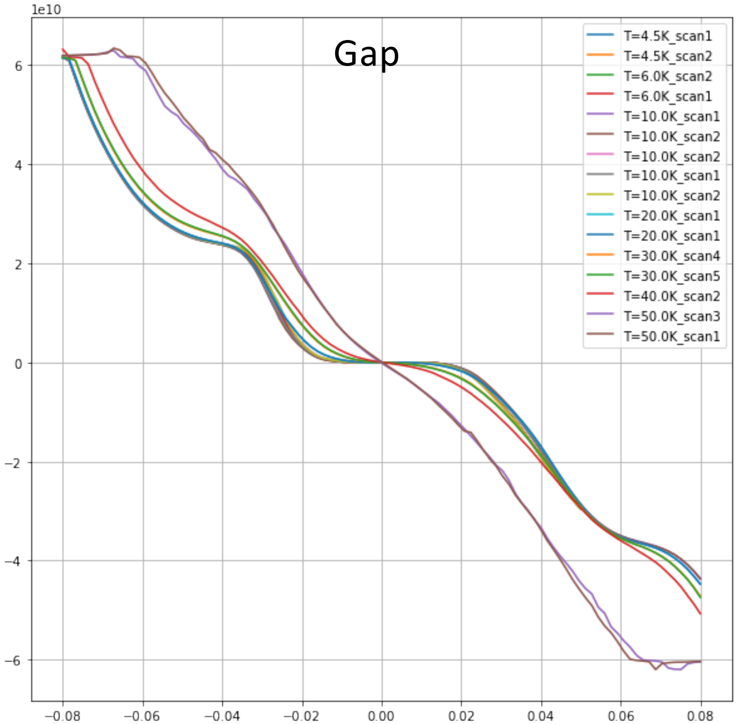


A160620.145933.X.dat

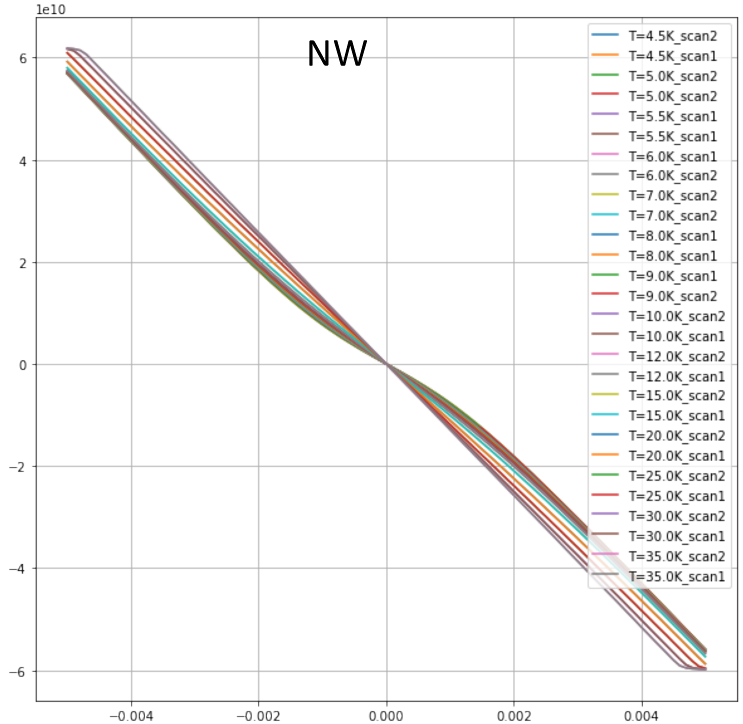
Fig. 4

full dataset

at T > 40K substrate leakage dominates conductance



slight non-linearity due to Schottky contacts in this device



D12_IV_NWGap(21-16)_04.5K001.dat D12_IV_NWGap(21-16)_10.0K005.dat D12_IV_NWGap(21-16)_04.5K002.dat D12_IV_NWGap(21-16)_20.0K001.dat
D12_IV_NWGap(21-16)_06.0K001.dat D12_IV_NWGap(21-16)_20.0K002.dat D12_IV_NWGap(21-16)_06.0K002.dat D12_IV_NWGap(21-16)_30.0K001.dat
D12_IV_NWGap(21-16)_10.0K001.dat D12_IV_NWGap(21-16)_30.0K002.dat D12_IV_NWGap(21-16)_10.0K002.dat D12_IV_NWGap(21-16)_40.0K001.dat
D12_IV_NWGap(21-16)_10.0K003.dat D12_IV_NWGap(21-16)_50.0K001.dat D12_IV_NWGap(21-16)_10.0K004.dat D12_IV_NWGap(21-16)_50.0K002.dat

Fig. 4 **Determination of the activation energy for the gap section of the device**

Fit Procedure for activation energy:

- fit polygon (polygon order n = 14 to 23) to region around $|V_{bias}|$ < co = 30, 32, 34, 36, 38, 40 mV
- analytically take derivative of polygon
- average conductance over region $|V_{bias}|$ < 5mV
- fit average conductance values as a function of temperature
- vary n and co in the range specified above to check robustness of fit

The plot below shows the activation energy for the different parameter variations and yields the uncertainty of +/- 5meV stated in the paper for the activation energy.

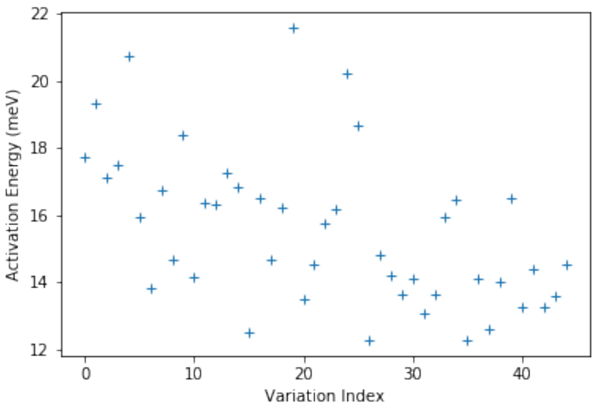
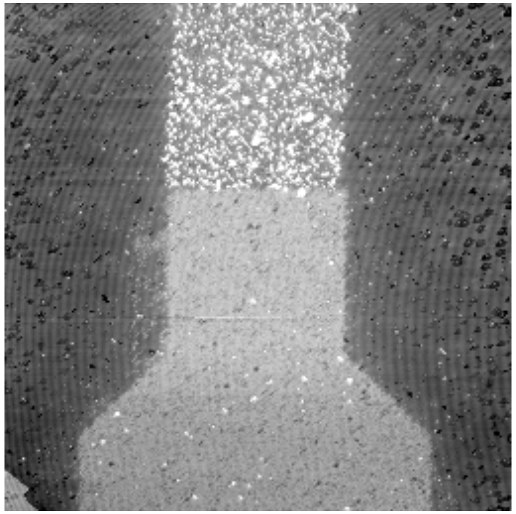
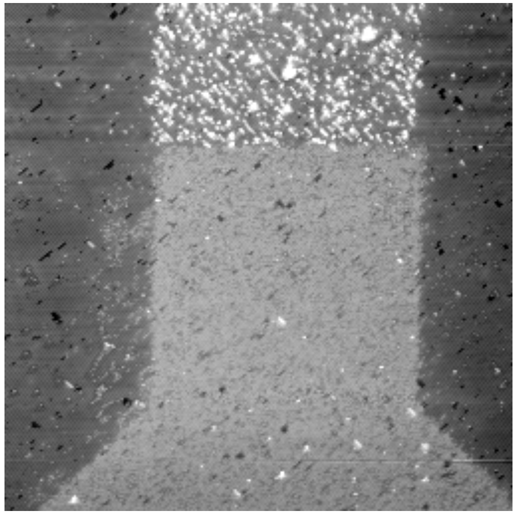


Fig. 5

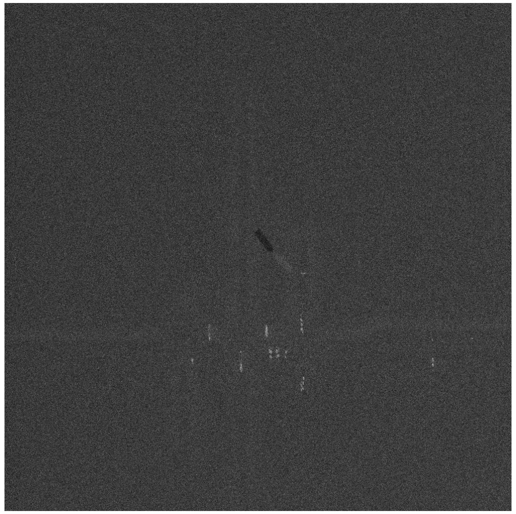
raw SEM and STM images of device



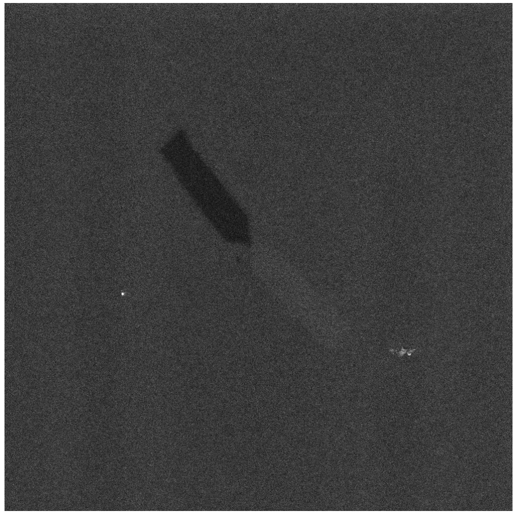
A160330.144902.dat



A160330.143938.dat



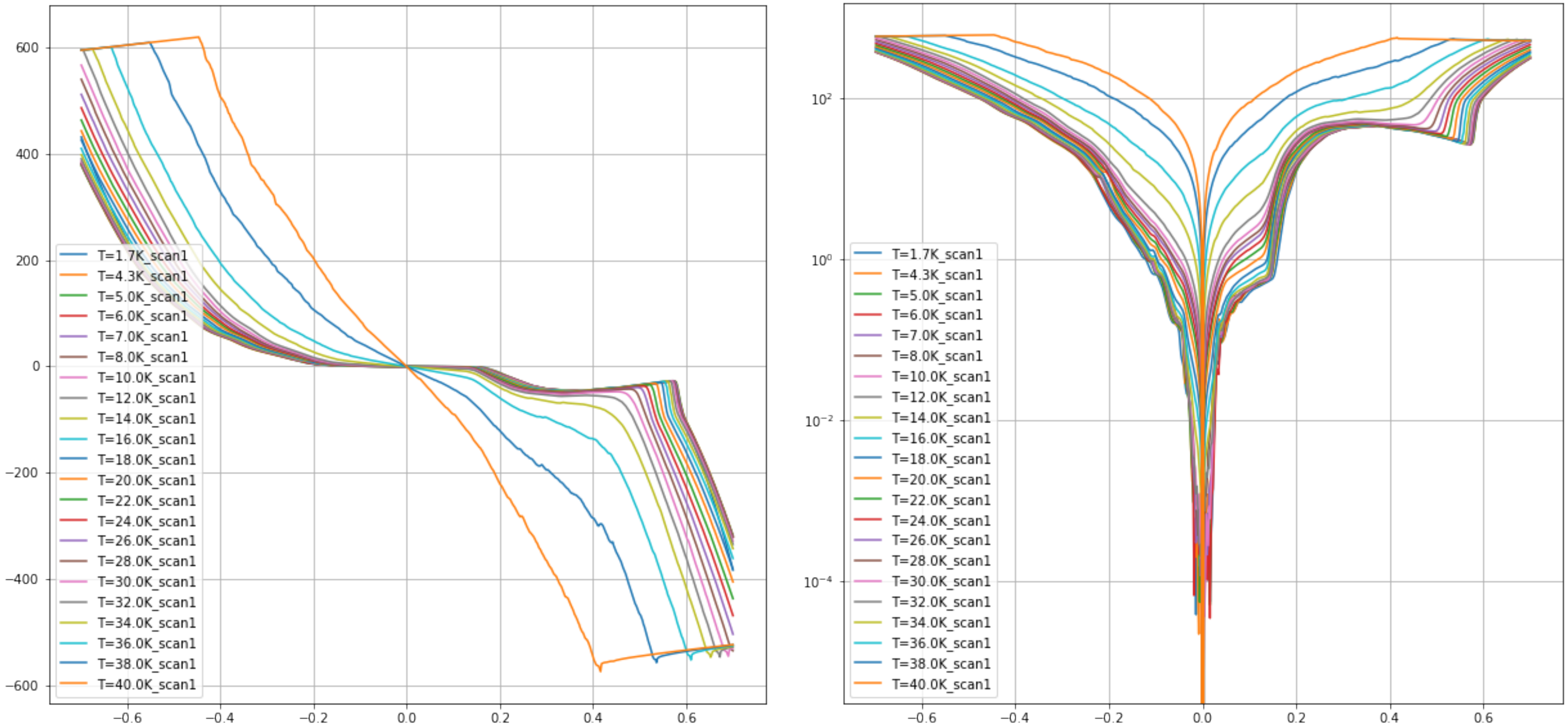
sem_pn_device_overv.pdf



sem_pn_device_zoom.pdf

Fig. 5

full dataset



D02_IV_curve_10M_03-04_01.7K001.dat D02_IV_curve_10M_03-04_20.0K001.dat D02_IV_curve_10M_03-04_04.3K001.dat D02_IV_curve_10M_03-04_22.0K001.dat D02_IV_curve_10M_03-04_05.0K001.dat D02_IV_curve_10M_03-04_24.0K001.dat D02_IV_curve_10M_03-04_06.0K001.dat D02_IV_curve_10M_03-04_26.0K001.dat D02_IV_curve_10M_03-04_07.0K001.dat D02_IV_curve_10M_03-04_28.0K001.dat D02_IV_curve_10M_03-04_08.0K001.dat D02_IV_curve_10M_03-04_30.0K001.dat D02_IV_curve_10M_03-04_10.0K001.dat D02_IV_curve_10M_03-04_32.0K001.dat D02_IV_curve_10M_03-04_12.0K001.dat D02_IV_curve_10M_03-04_34.0K001.dat D02_IV_curve_10M_03-04_14.0K001.dat D02_IV_curve_10M_03-04_36.0K001.dat D02_IV_curve_10M_03-04_16.0K001.dat D02_IV_curve_10M_03-04_38.0K001.dat D02_IV_curve_10M_03-04_18.0K001.dat D02_IV_curve_10M_03-04_40.0K001.dat