THE SiC/SiO_2 INTERFACE STRUCTURE

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DARPA/EPRI MEGAWATT REVIEW

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Overview

1) The focus of our effort has been to improve the characteristics (defect density) of the SiC/SiO_2 interface, which currently limits the useful range of 4H-SiC Power MOSFETS.

2) At the previous meeting in this series we reported the significant finding that a substantial decrease in defect density, D_{it}, of this interface results from annealing in nitrogen ambients. These effects were explained in terms of nitrogen induced passivation of carbon (cluster) defects.

3) In this session we report results which build on this nitrogen process. In particular, we show:
   - **i) Quantitative measures of N incorporation as a function of time and temperature;**
   - **ii) New D_{it} data which explores the N effect as a function of defect position in the band-gap;**
   - **iii) MOSFET mobility data, showing significant mobility improvement due to N;**
   - iv) **Theory, explaining the N band-gap dependence and C-O removal.**

Nitrogen Incorporation

1. NO process-

D (units)= 1.0E11/cm2 eV

G.Y. Chung et al. APL,76, 1713(2000)

μ (units)=cm²/Vsec

4H-$D_{it}(E_c)$=25, μ_{4H}=35-70

2.NH3 process-

G.Y.Chung et al APL (to be published)

4H-$D_{it}(E_c)$=20, μ_{4H}=?

3. N_2O-process-

Dimitrijev et al. EDL, 18, 175 (1997)

6H-$D_{it}(O_2)$=1.1, $D_{it}(O_2+NO)$=0.3, $D_{it}(O_2+N_2O)$=1.3; μ=?

4. N ion implantation-not reported (?)

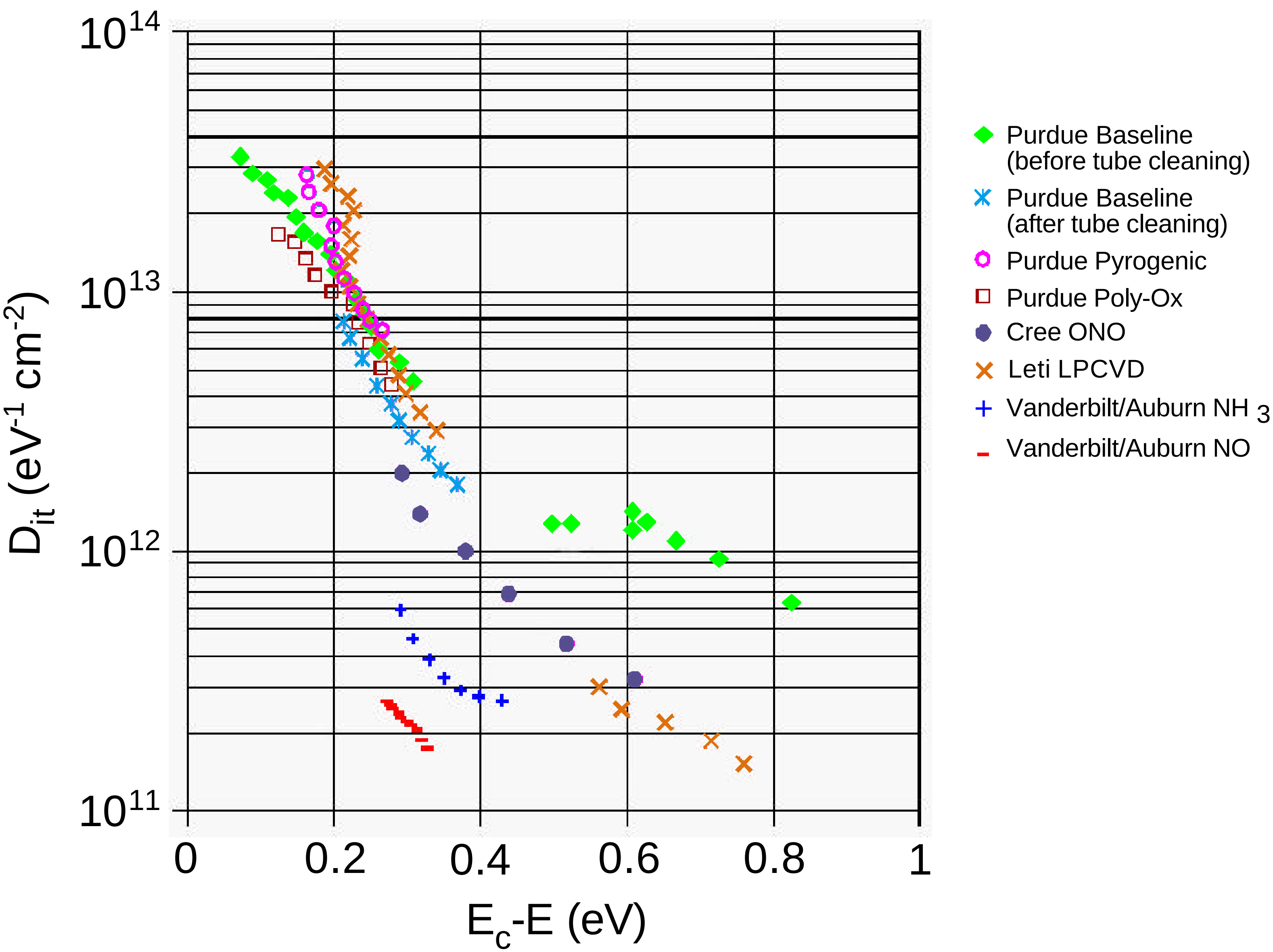
Sridevan and Baliga, Matls.Sci Forum, **264**, 997 (1998)

μ_{4H}=160; μ_{6H}=110; N_{eff}=5.0

5.Deposited oxynitrides-

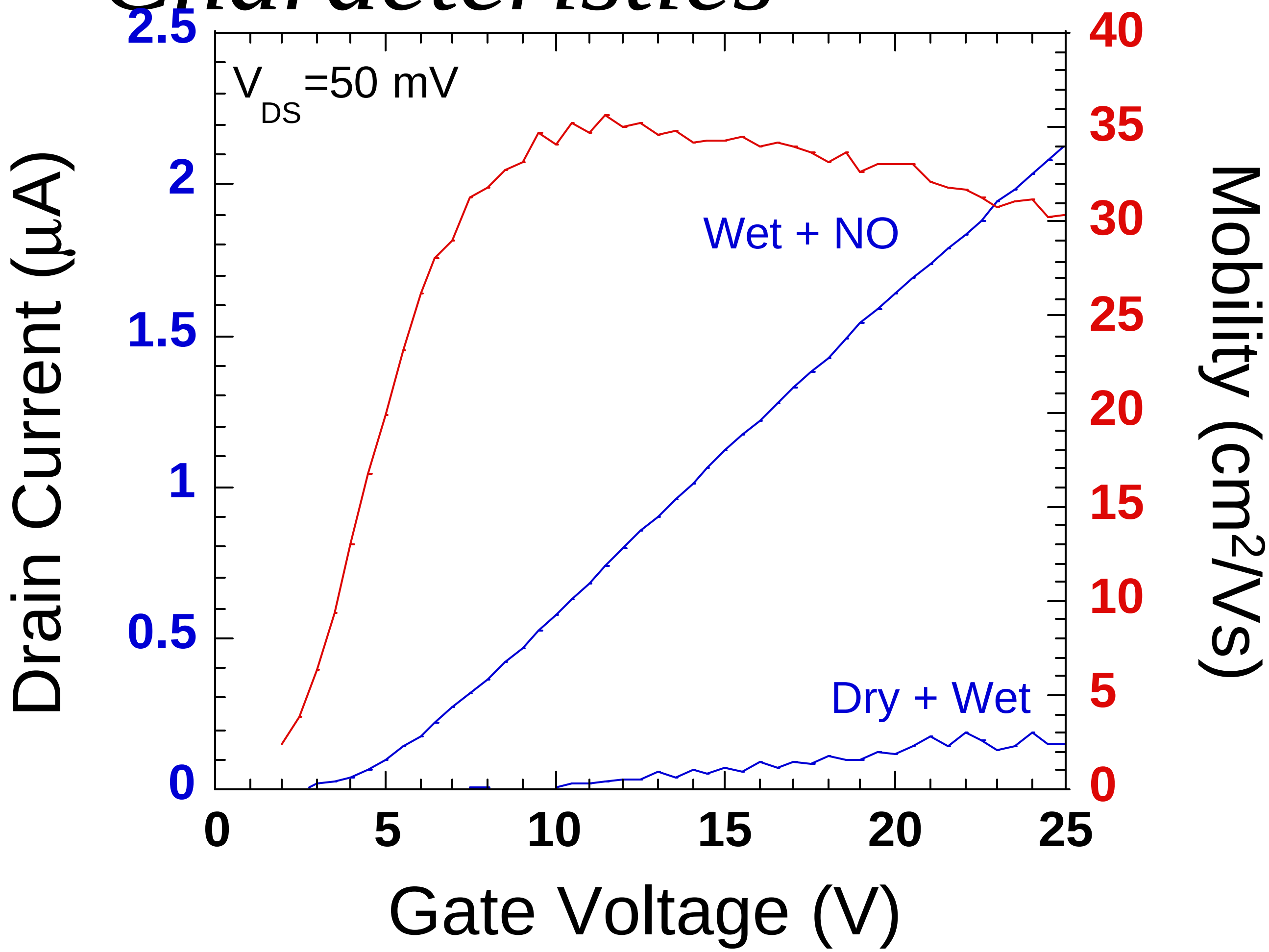
Ma et al (JVD);Lipkin and Palmour (ISCRM)

μ_{4H}(ONO)=40, μ_{4H}(O)=35



10^{14}
10^{13}
10^{12}
10^{11}
D_{it} (eV^{-1} cm^{-2})
0
0.2
0.4
0.6
0.8
1
E_c-E (eV)
Purdue Baseline
(before tube cleaning)
Purdue Baseline
(after tube cleaning)
Purdue Pyrogenic
Purdue Poly-Ox
Cree ONO
Leti LPCVD
Vanderbilt/Auburn NH_3
Vanderbilt/Auburn NO

4H-SiC MOSFET Transfer Characteristics



OUTSTANDING 4H-MOBILITY RESULTS

1. 165 cm^2/Vsec; Sridevan and Baliga, EDL 19,228 (1998)

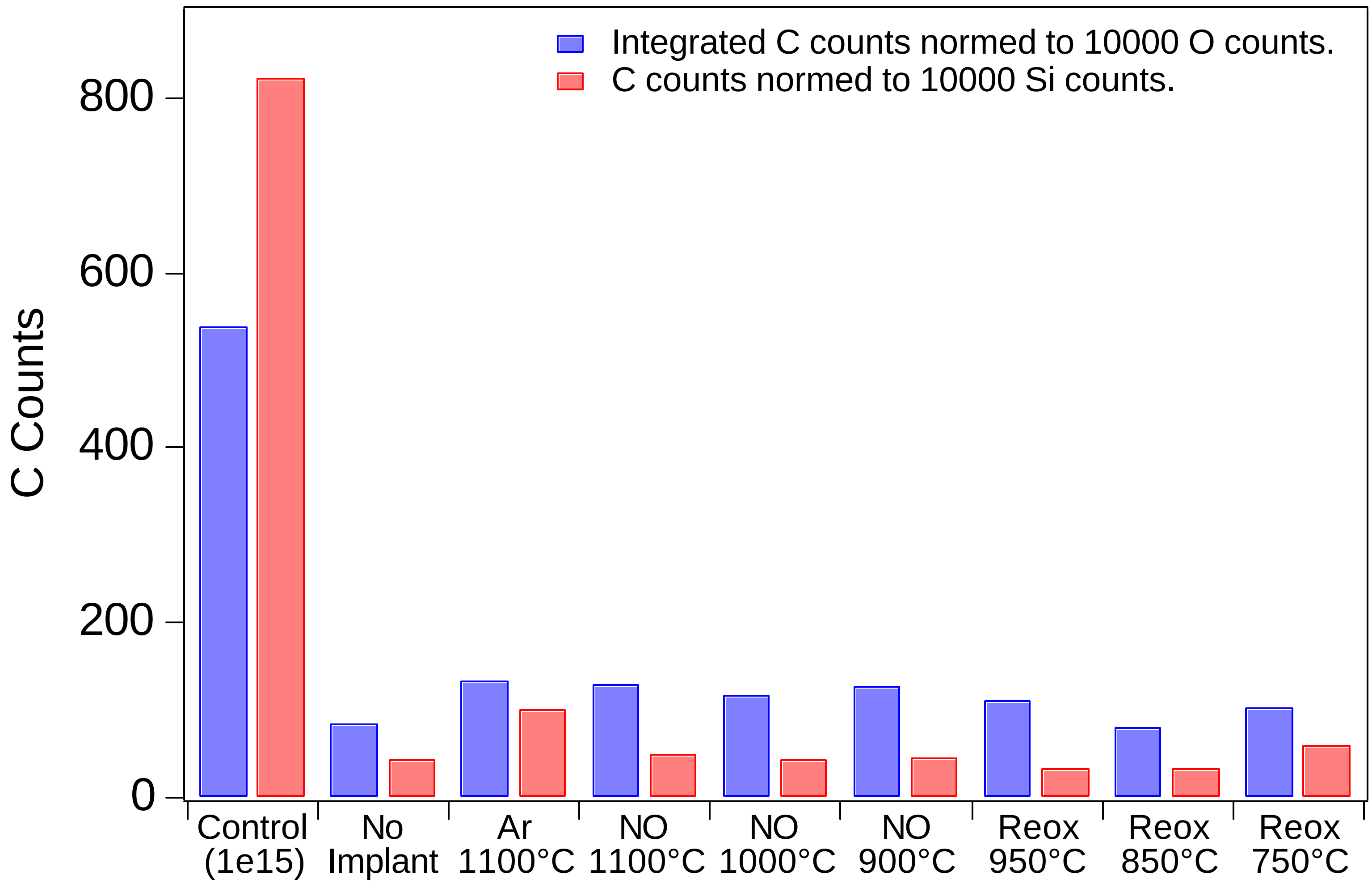
   Possibly a buried channel device due to nitrogen implantation. R_p (40Kev N/SiO_2)=800A+-300A with a 1000A oxide.

2. 96cm^2/Vsec; Yano et al, Jap,J. Appl. Phys. 39, (2000)

   (1120) face, non-polar surface.

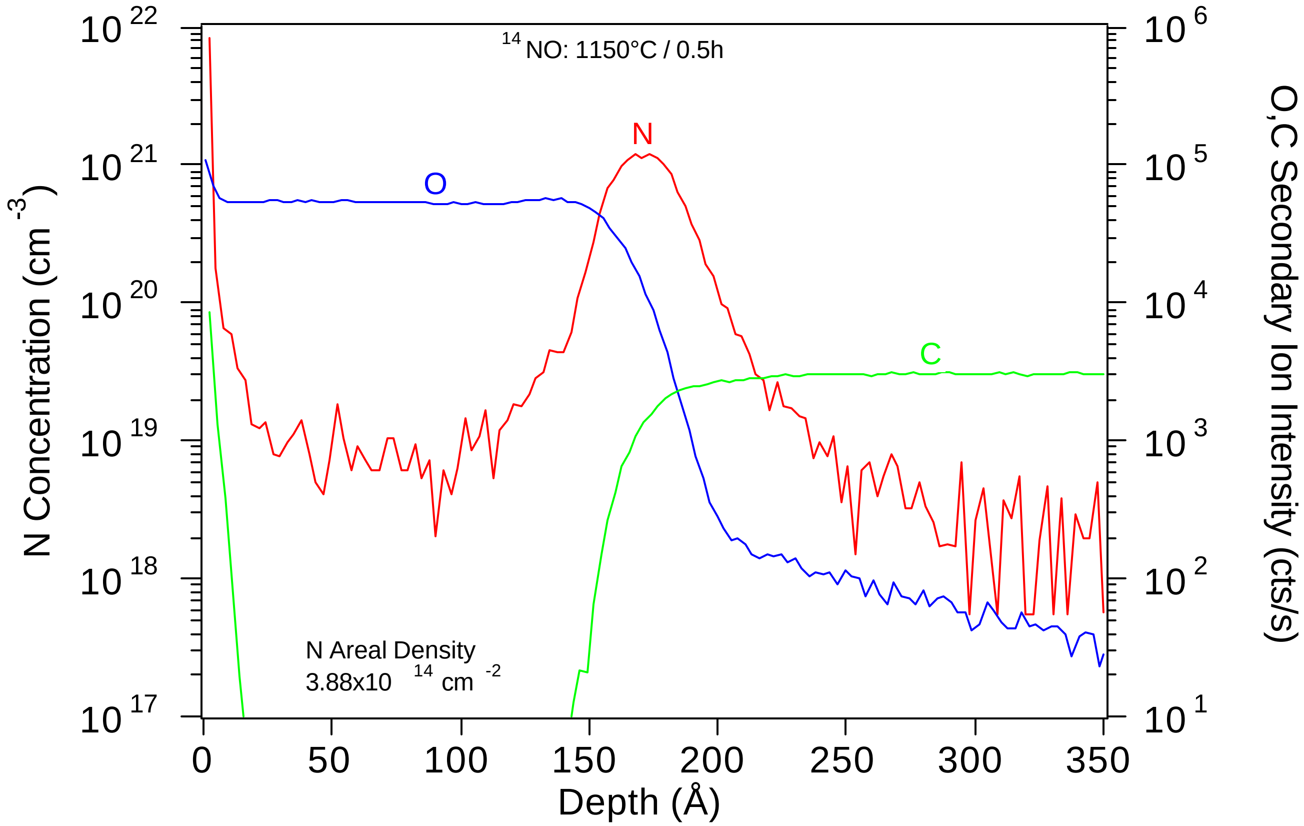
3. 35-70cm^2/Vsec; Das, Chung, McDonald et al. APL, EDL (2000)

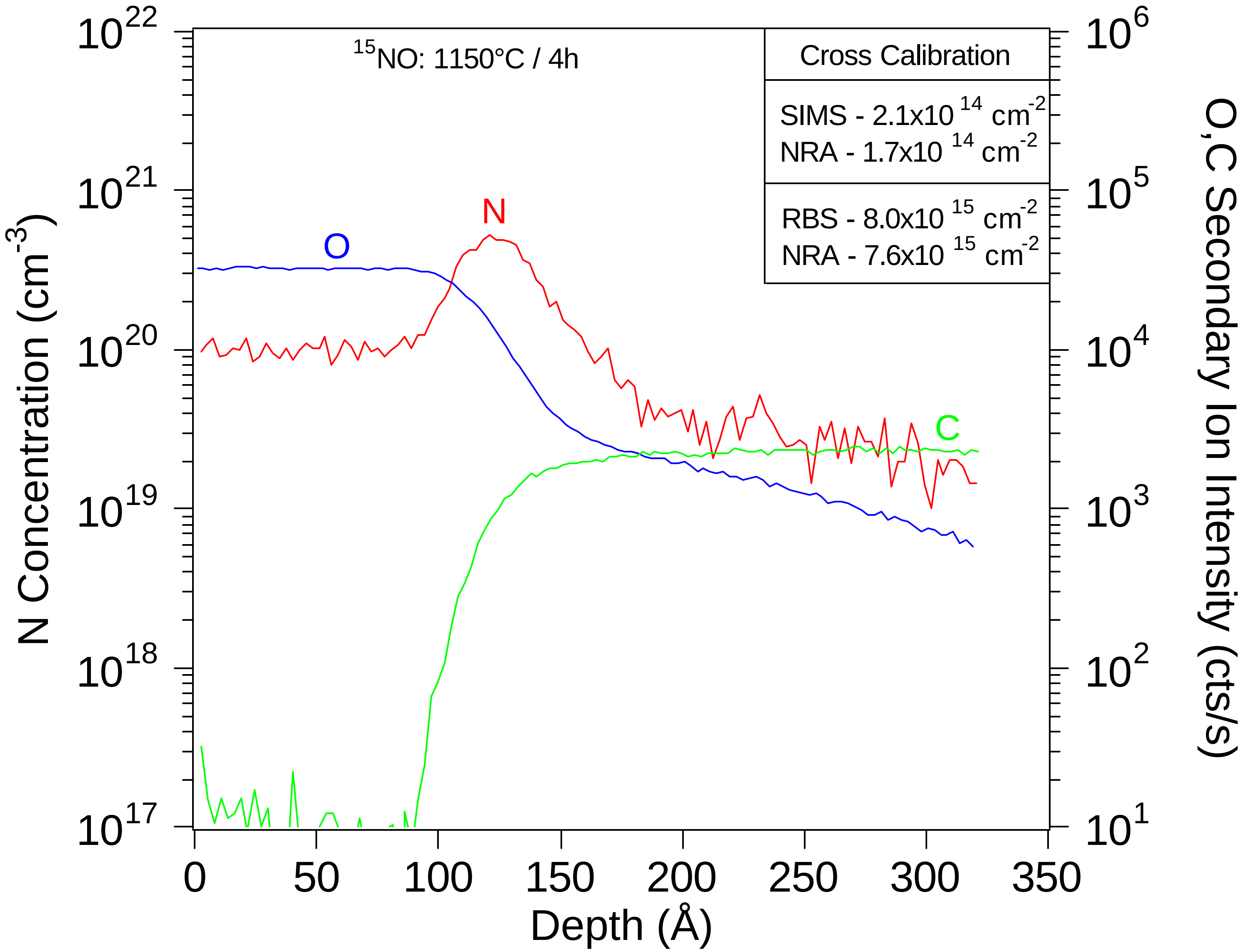
   NO annealing after oxidation.


Integrated C counts normed to 10000 O counts.
C counts normed to 10000 Si counts.
C Counts
0
200
400
600
800
Control (1e15)
No Implant
Ar 1100°C
NO 1100°C
NO 1000°C
NO 900°C
Reox 950°C
Reox 850°C
Reox 750°C

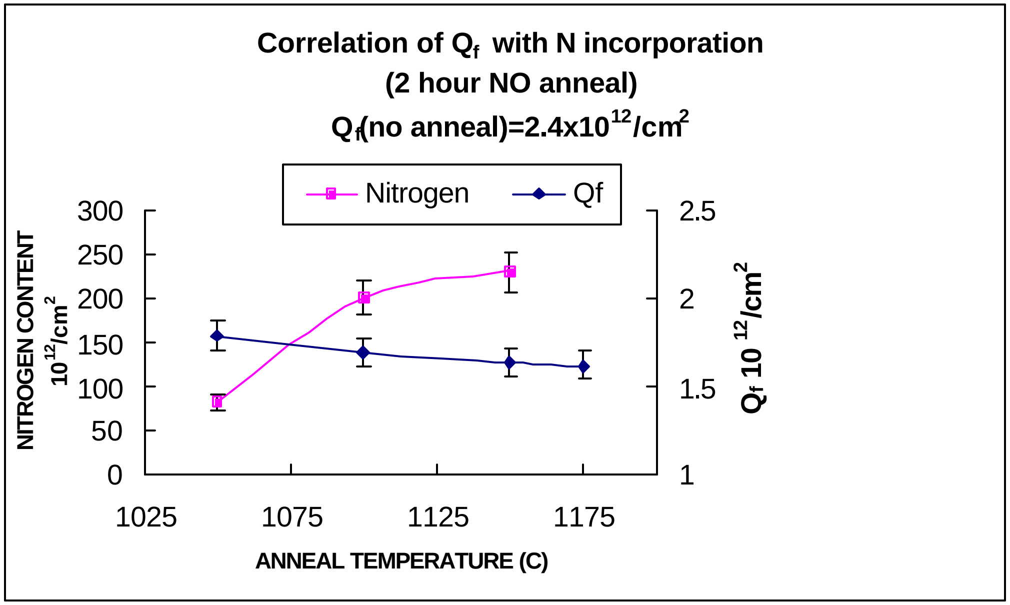
Secondary Ion Mass Spectrometry

Interface nitrogen incorporation from NO annealing process

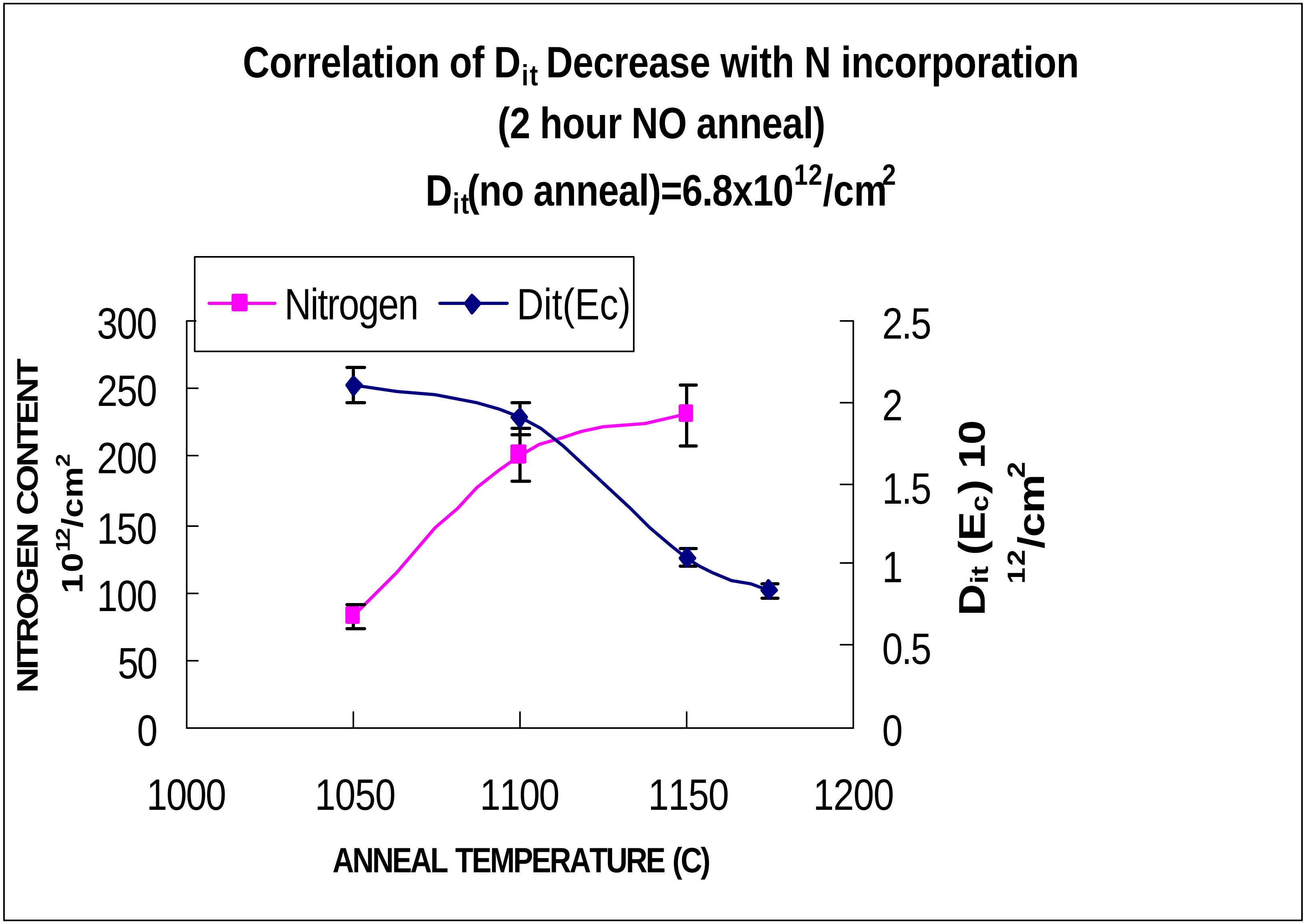




^{15}NO: 1150°C / 4h
Cross Calibration
SIMS - 2.1x10^{14} cm^{-2}
NRA - 1.7x10^{14} cm^{-2}
RBS - 8.0x10^{15} cm^{-2}
NRA - 7.6x10^{15} cm^{-2}
O
N
C
N Concentration (cm^{-3})
O,C Secondary Ion Intensity (cts/s)
Depth (Å)
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
0
50
100
150
200
250
300
350



Correlation of Qf with N incorporation
(2 hour NO anneal)
Qf(no anneal)=2.4x10^12/cm^2
Nitrogen
Qf
NITROGEN CONTENT 10^12/cm^2
Qf 10^12/cm^2
300
250
200
150
100
50
0
2.5
2
1.5
1
1025
1075
1125
1175
ANNEAL TEMPERATURE (C)



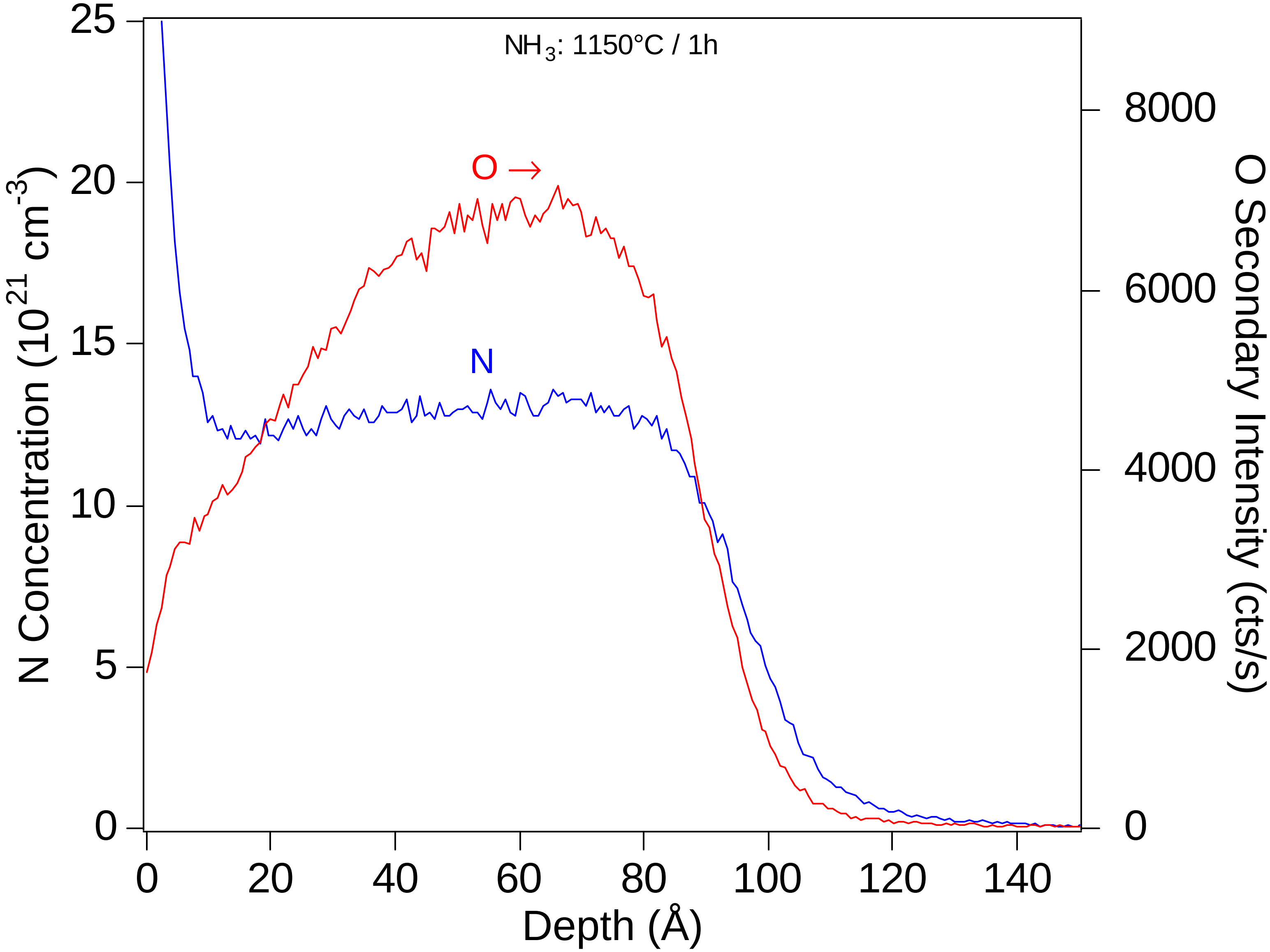
Correlation of D_{it} Decrease with N incorporation
(2 hour NO anneal)
D_{it}(no anneal)=6.8x10^{12}/cm^2
Nitrogen
Dit(Ec)
NITROGEN CONTENT 10^{12}/cm^2
D_{it} (E_c) 10^{12}/cm^2
300
250
200
150
100
50
0
2.5
2
1.5
1
0.5
0
1000
1050
1100
1150
1200
ANNEAL TEMPERATURE (C)

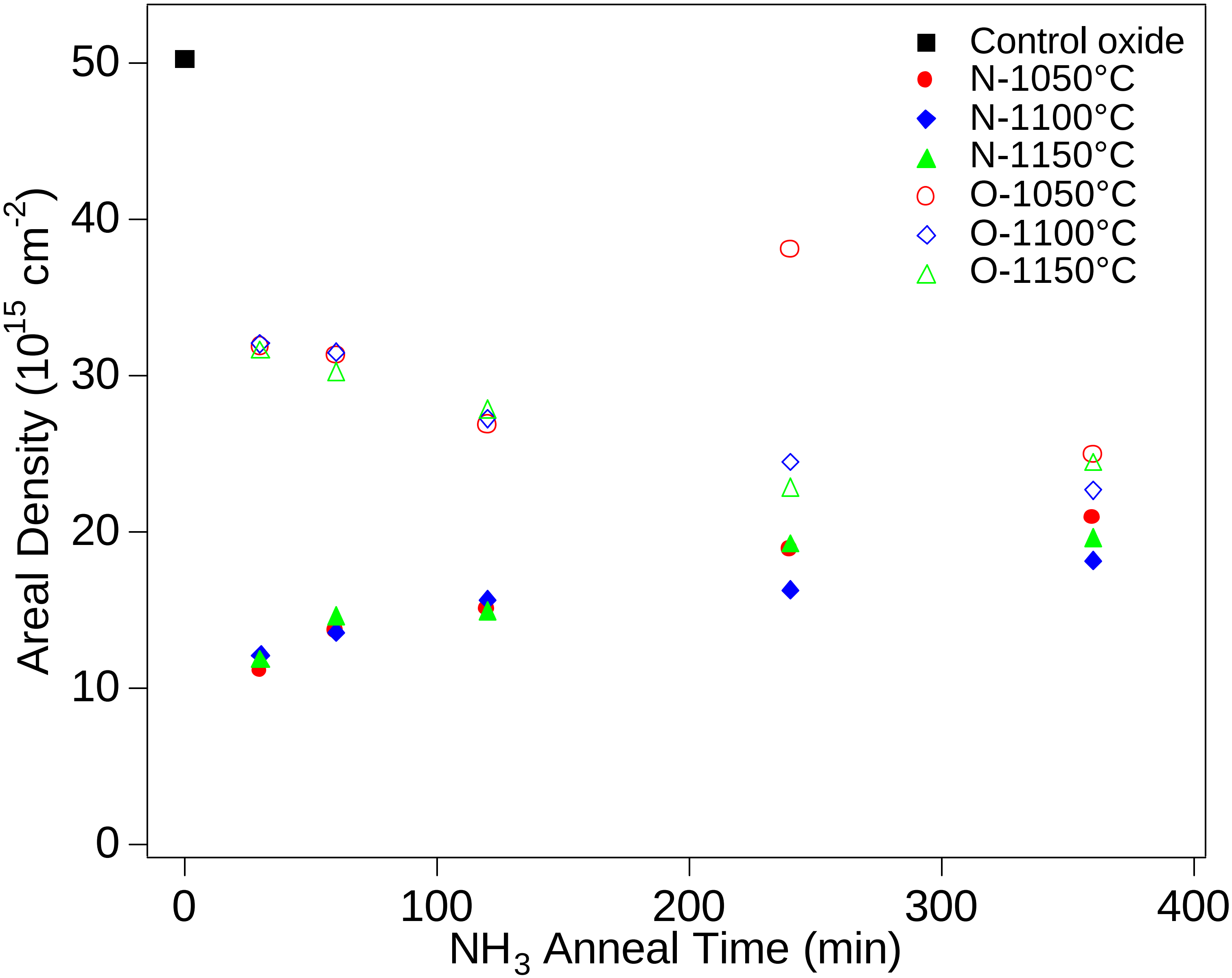
Nitrogen at the Interface?

1. **Stress relaxation**- thermal expansion difference and "atom density" cause stress. Even though the nitride-silicon difference is of opposite sign to the oxide-silicon difference there is not enough nitrogen to make this plausible.

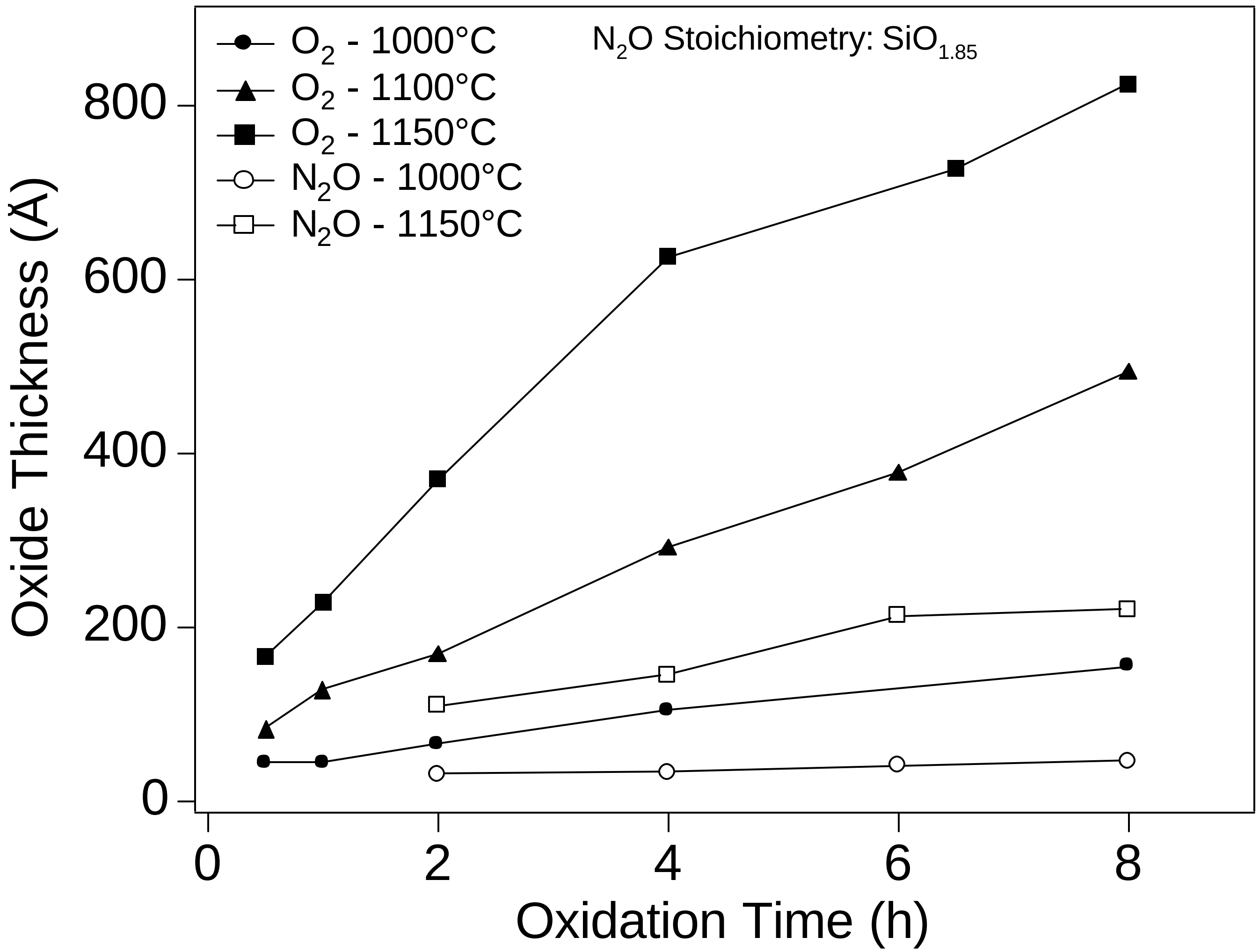
2.**Interface chemistry**-molecular orbital calculations for silicon indicate that interface chemistry is the predominant driving force for interfacial silicon. (Ushio et al., APL 75, 680, (1999). Note that Ushio also calculate stress (for Si/SiO_2 and show it does not work. Si/SiO_2 stress is comparable to SiC/SiO_2.

3.**Voids-**positrons see voids at the Si/SiO_2 interface. Possibly the nitrogen species is simply filling voids.

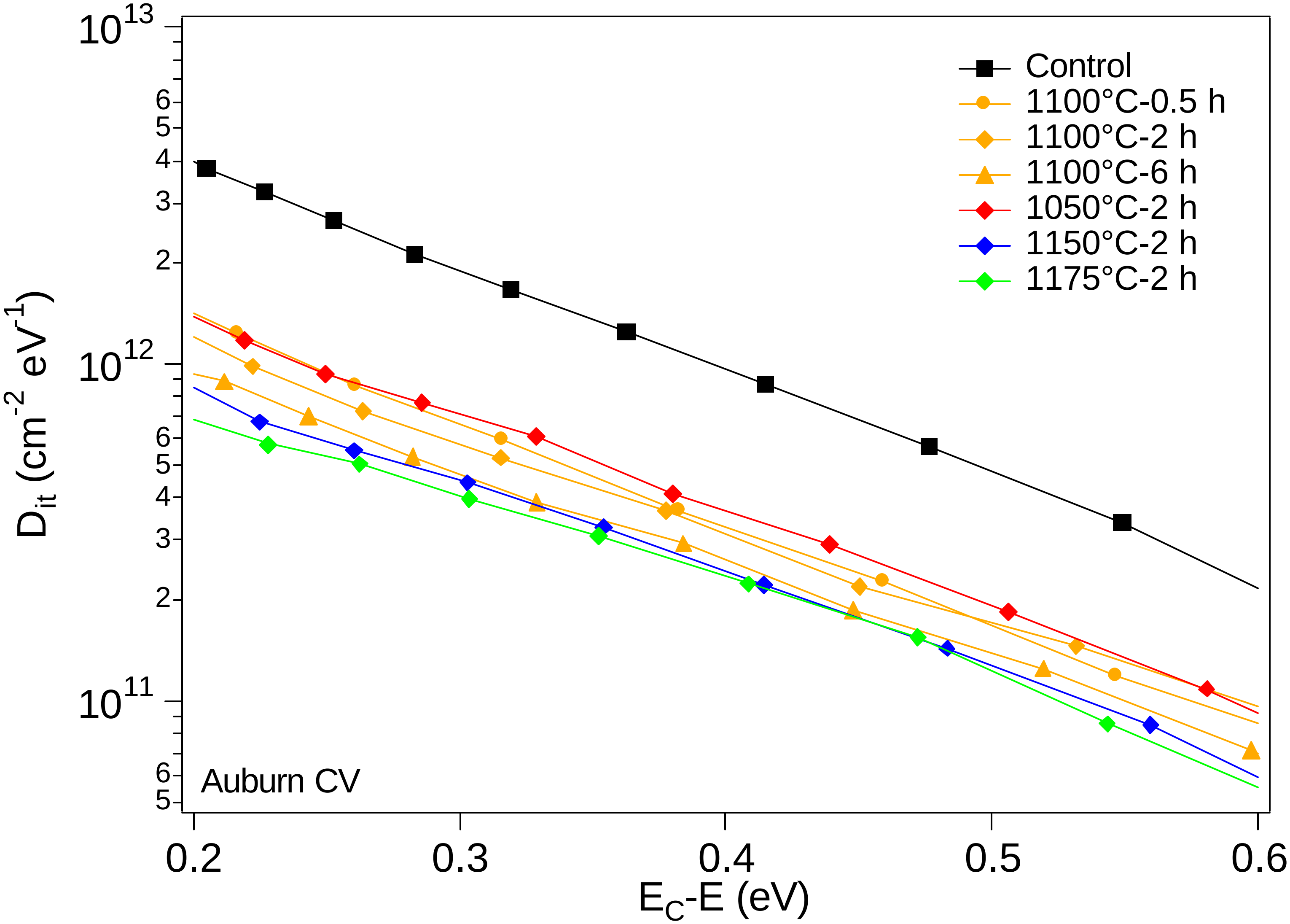

NH$_3$: 1150°C / 1h
O →
N
N Concentration (10^{21} cm^{-3})
O Secondary Intensity (cts/s)
Depth (Å)
0
5
10
15
20
25
0
2000
4000
6000
8000
0
20
40
60
80
100
120
140



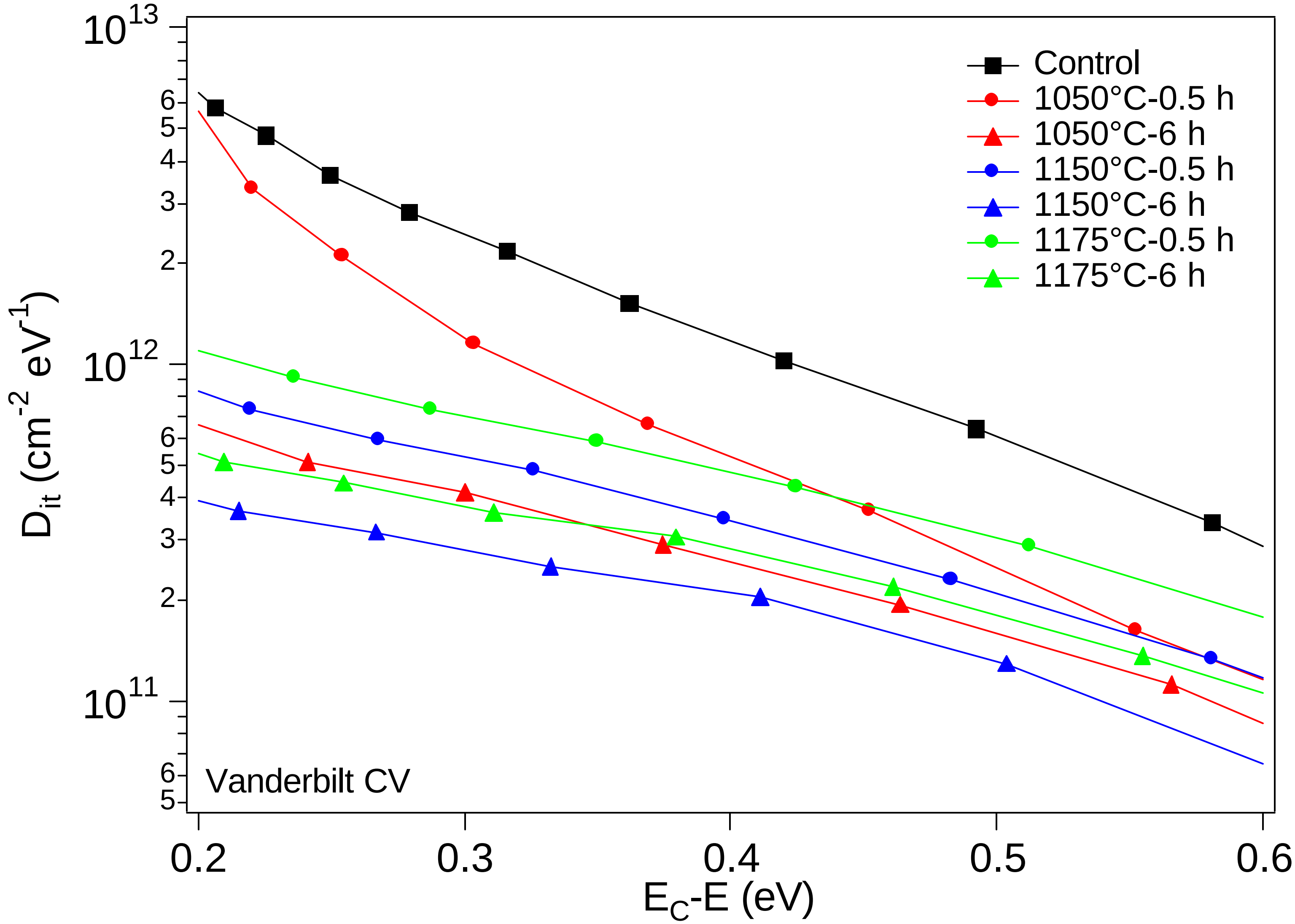
Control oxide
N-1050°C
N-1100°C
N-1150°C
O-1050°C
O-1100°C
O-1150°C
Areal Density (10^{15} cm^{-2})
50
40
30
20
10
0
0
100
200
300
400
NH_3 Anneal Time (min)



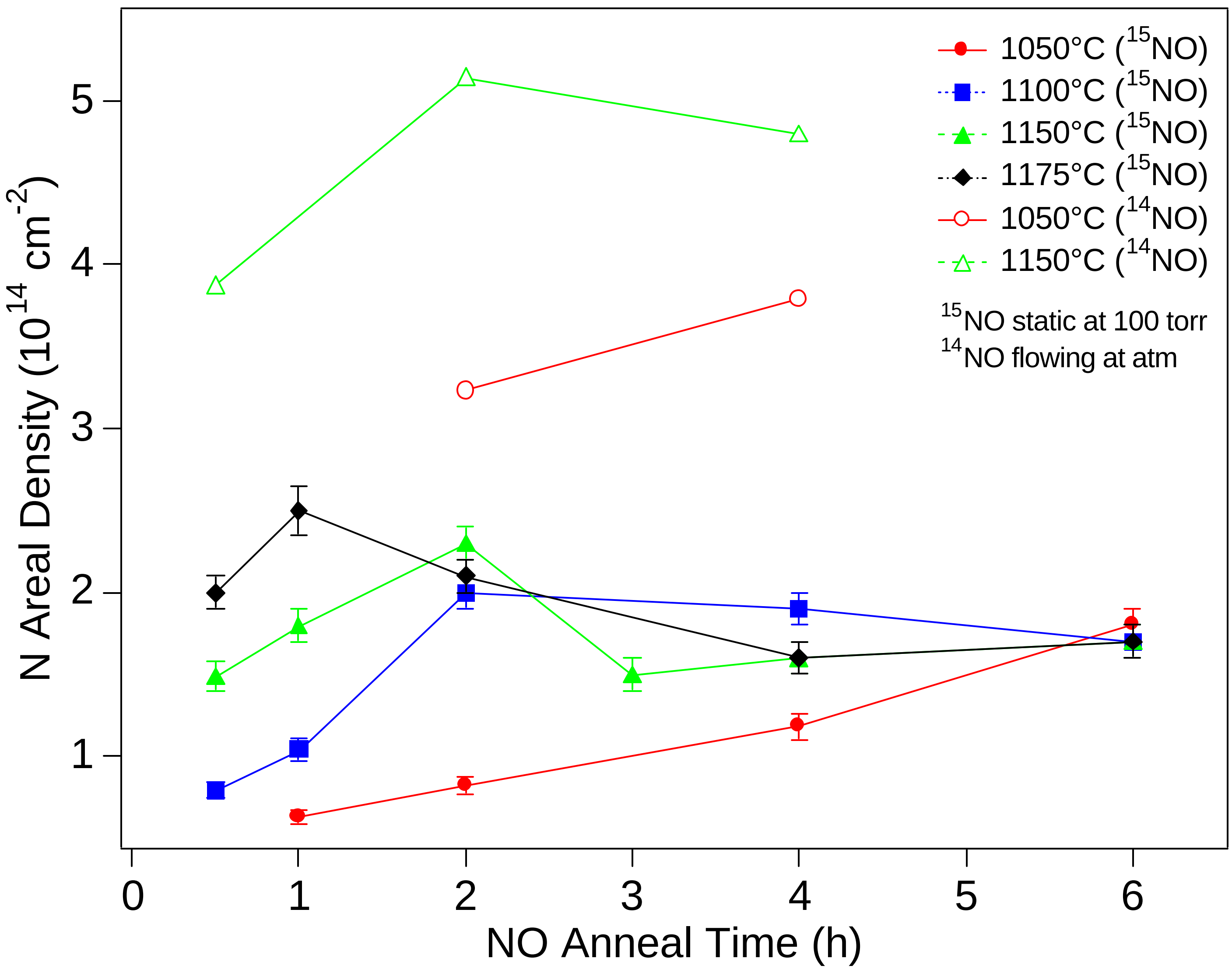
O2 - 1000°C
O2 - 1100°C
O2 - 1150°C
N2O - 1000°C
N2O - 1150°C
N2O Stoichiometry: SiO1.85
Oxide Thickness (Å)
0
200
400
600
800
0
2
4
6
8
Oxidation Time (h)



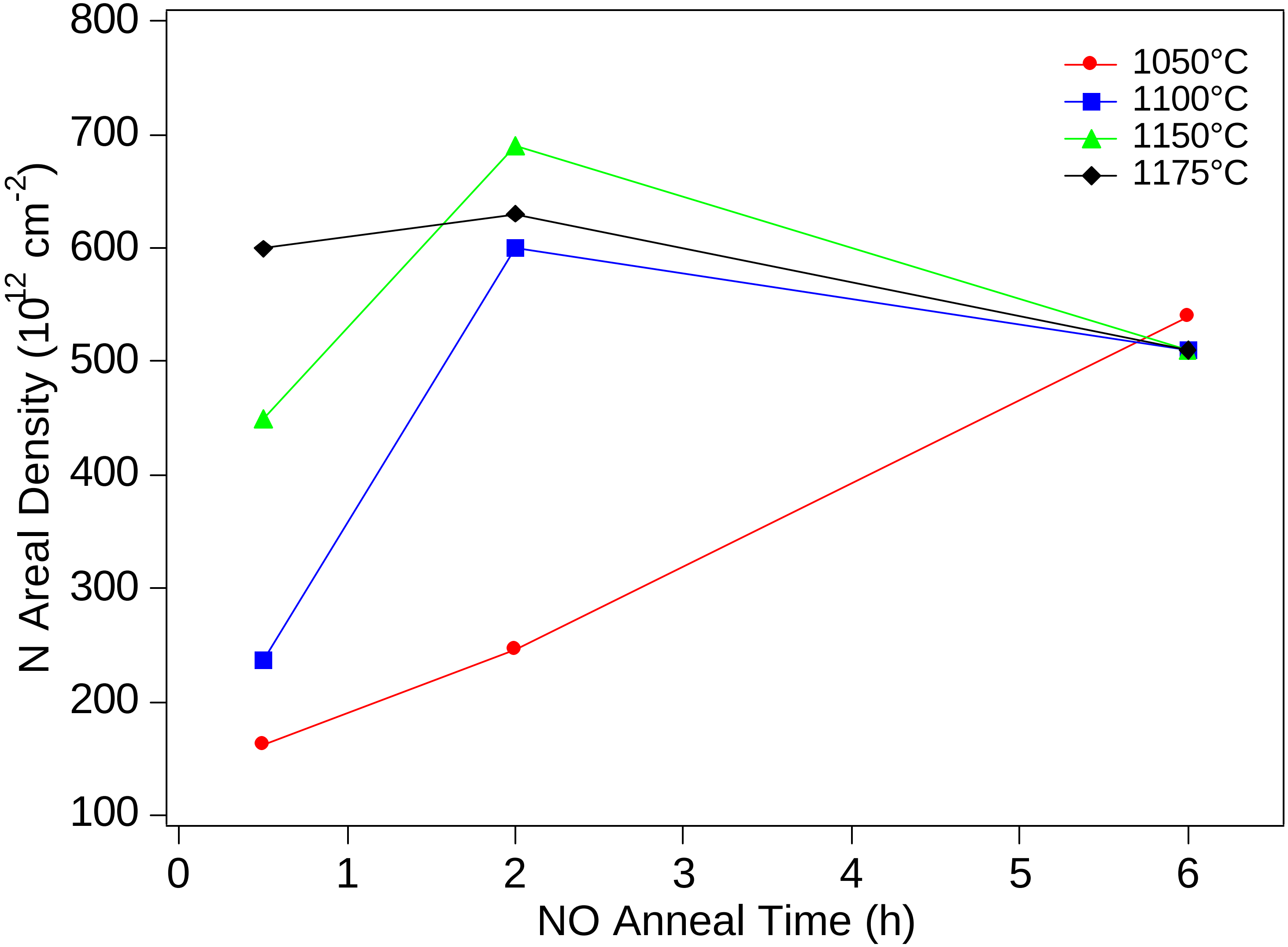
Control
1100°C-0.5 h
1100°C-2 h
1100°C-6 h
1050°C-2 h
1150°C-2 h
1175°C-2 h
Auburn CV
D_{it} (cm^{-2} eV^{-1})
E_C-E (eV)
10^{13}
10^{12}
10^{11}
6
5
4
3
2
0.2
0.3
0.4
0.5
0.6



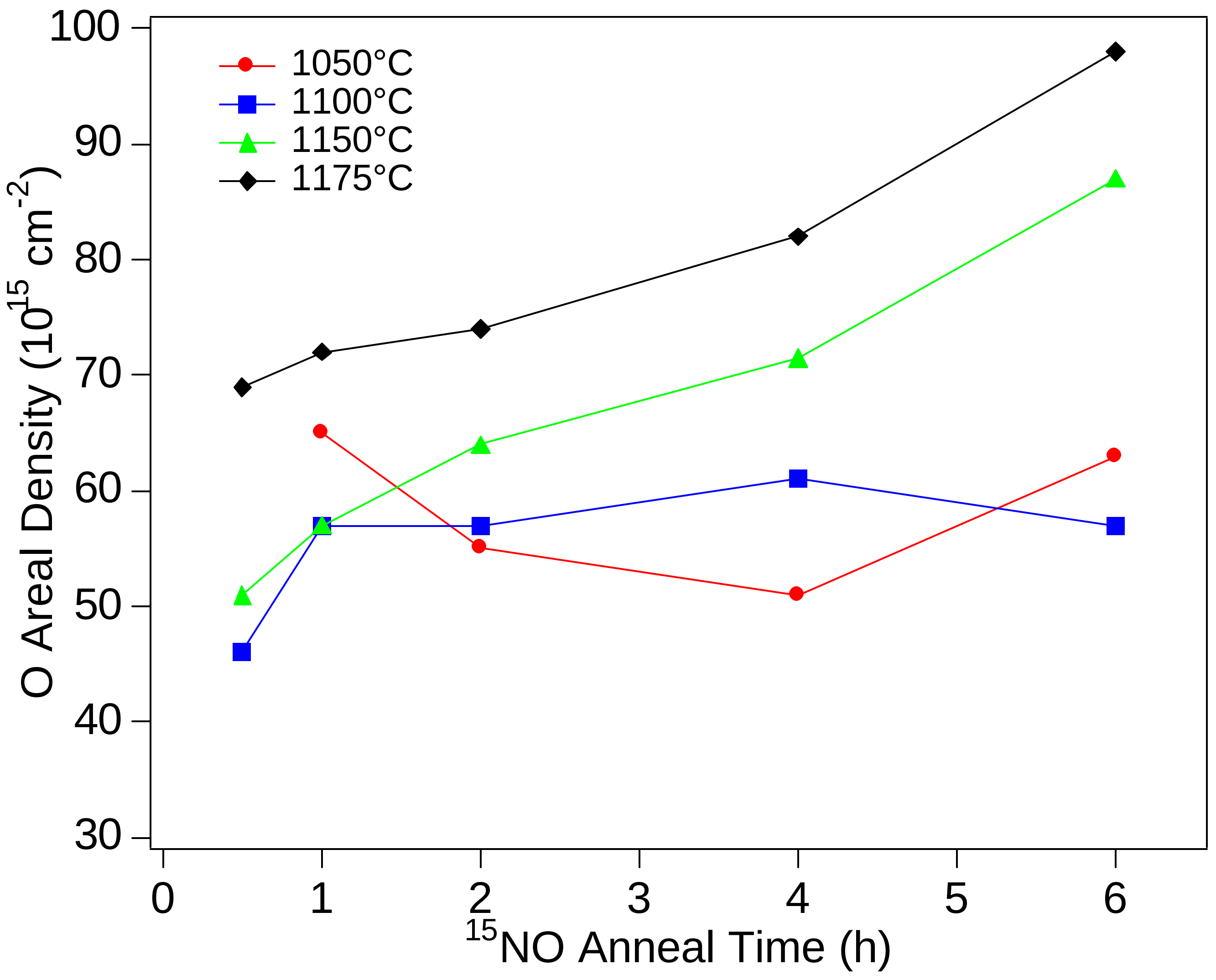
Control
1050°C-0.5 h
1050°C-6 h
1150°C-0.5 h
1150°C-6 h
1175°C-0.5 h
1175°C-6 h
Vanderbilt CV
D_{it} (cm^{-2} eV^{-1})
E_C-E (eV)
10^{13}
10^{12}
10^{11}
0.2
0.3
0.4
0.5
0.6



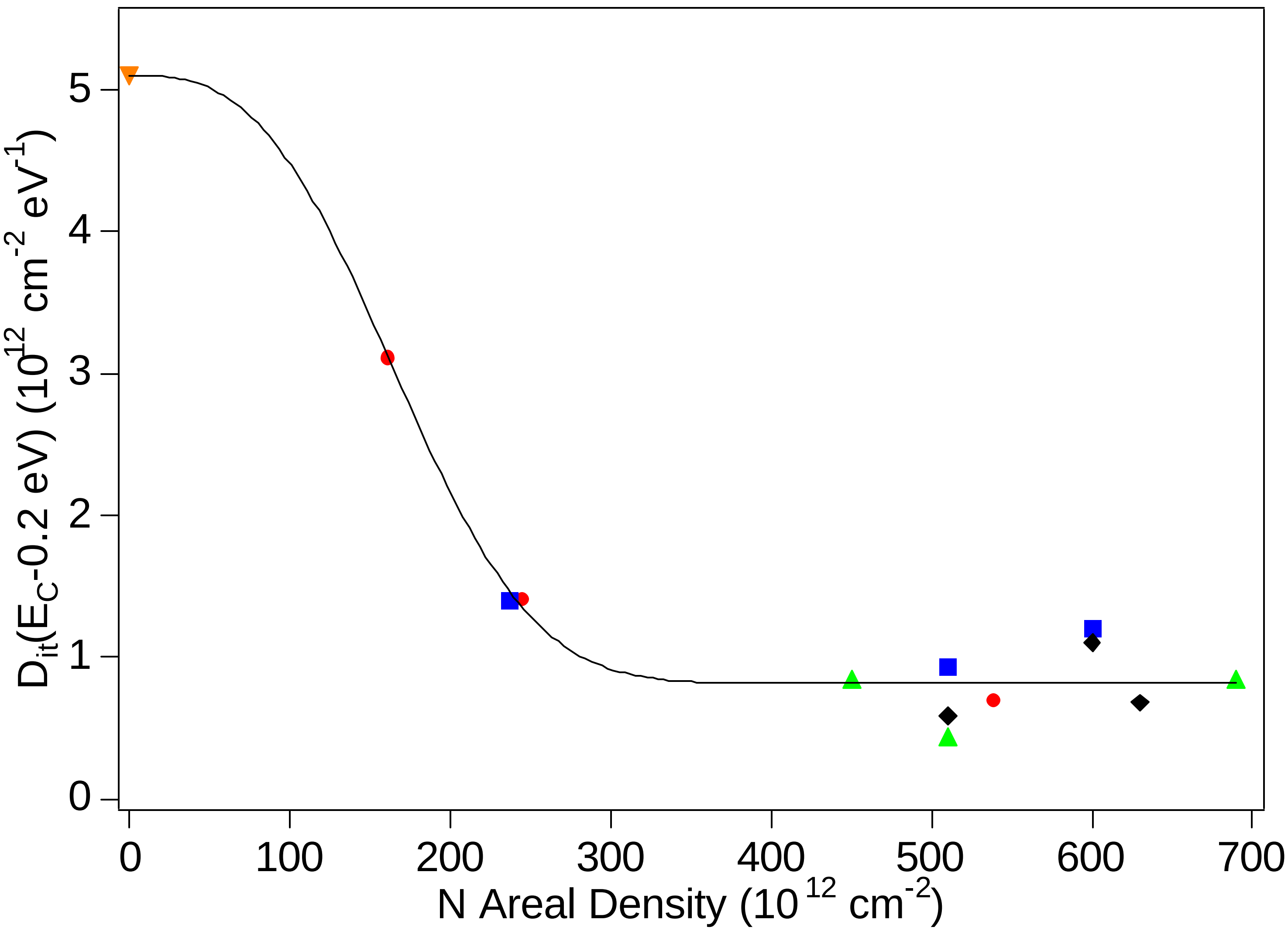
1050°C (^{15}NO)
1100°C (^{15}NO)
1150°C (^{15}NO)
1175°C (^{15}NO)
1050°C (^{14}NO)
1150°C (^{14}NO)
^{15}NO static at 100 torr
^{14}NO flowing at atm
N Areal Density (10^{14} cm^{-2})
NO Anneal Time (h)
0
1
2
3
4
5
6



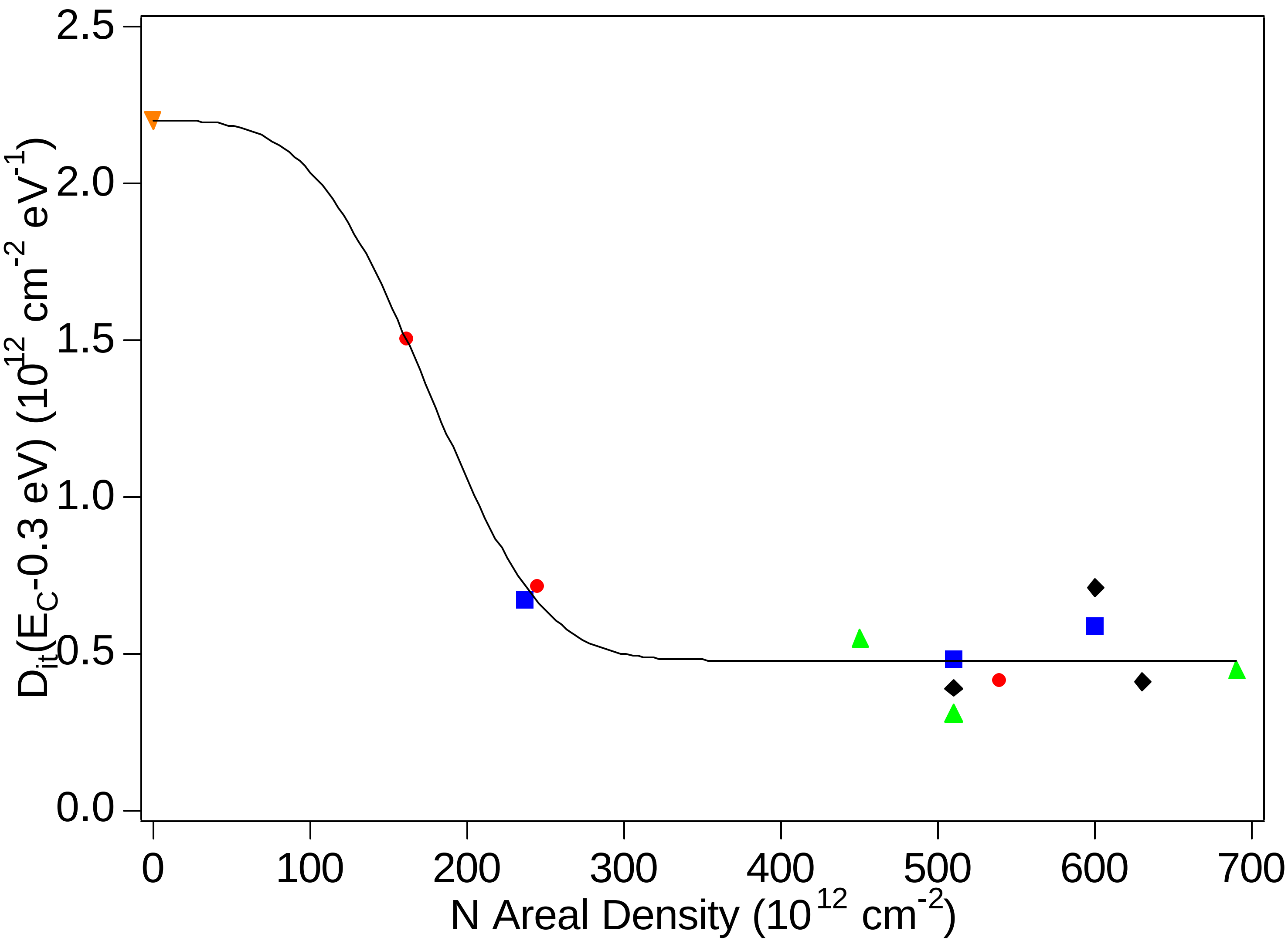
1050°C
1100°C
1150°C
1175°C
800
700
600
500
400
300
200
100
N Areal Density (10^{12} cm^{-2})
0
1
2
3
4
5
6
NO Anneal Time (h)



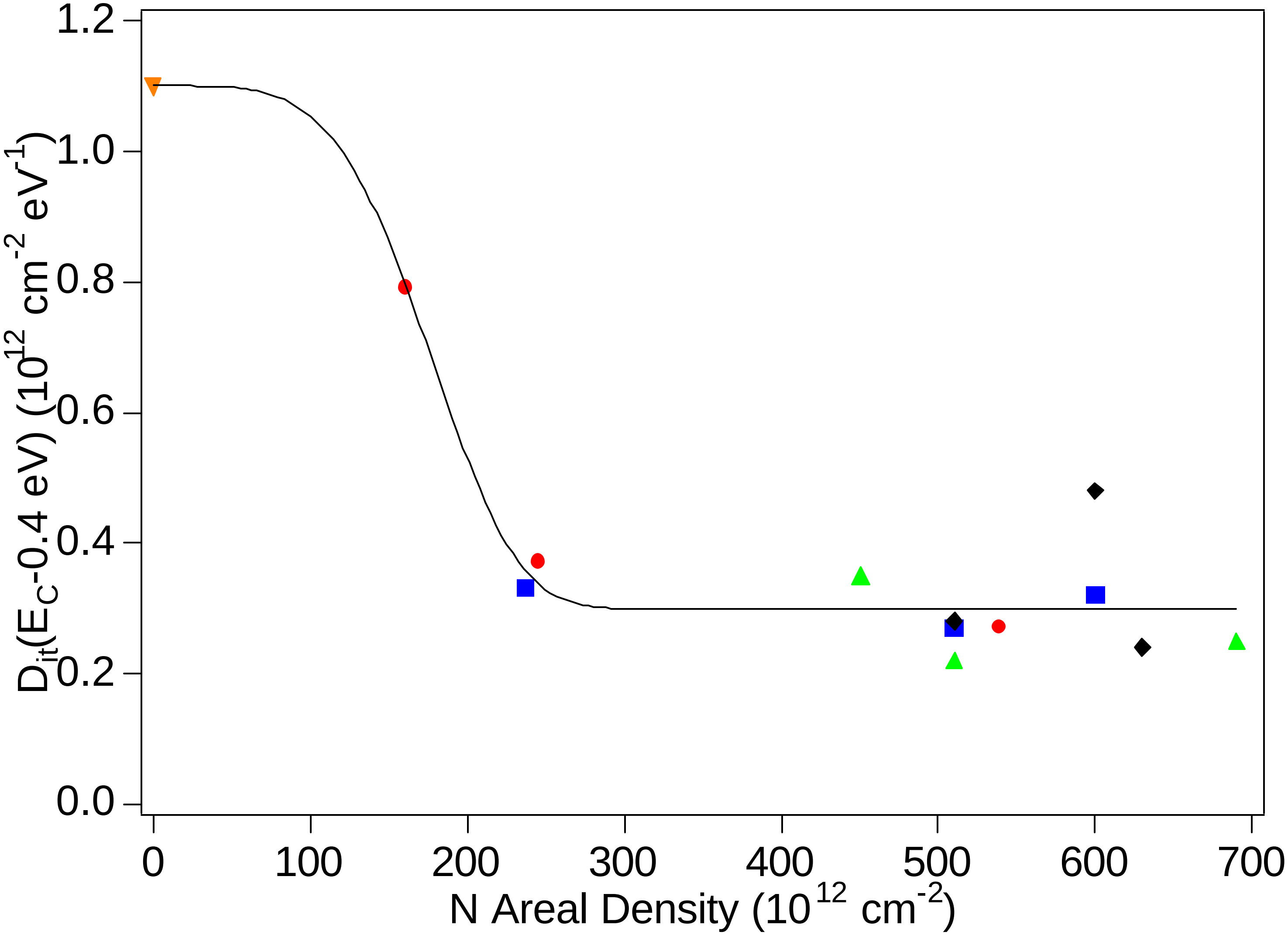
1050°C
1100°C
1150°C
1175°C
O Areal Density (10^{15} cm^{-2})
^{15}NO Anneal Time (h)
100
90
80
70
60
50
40
30
0
1
2
3
4
5
6



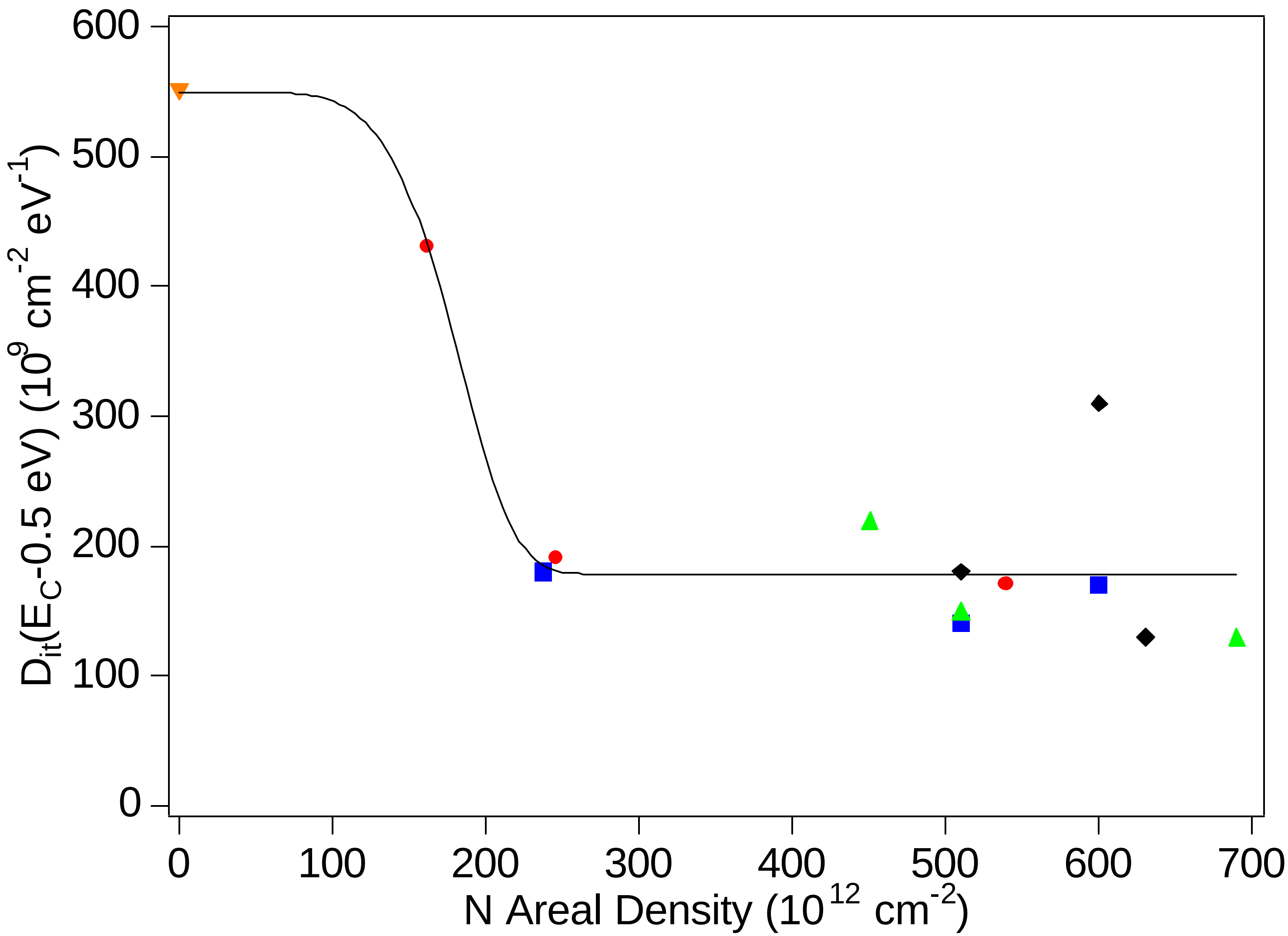
$D_{it}(E_C$-0.2 eV) (10^{12} cm^{-2} eV^{-1})
0
1
2
3
4
5
0
100
200
300
400
500
600
700
N Areal Density (10^{12} cm^{-2})



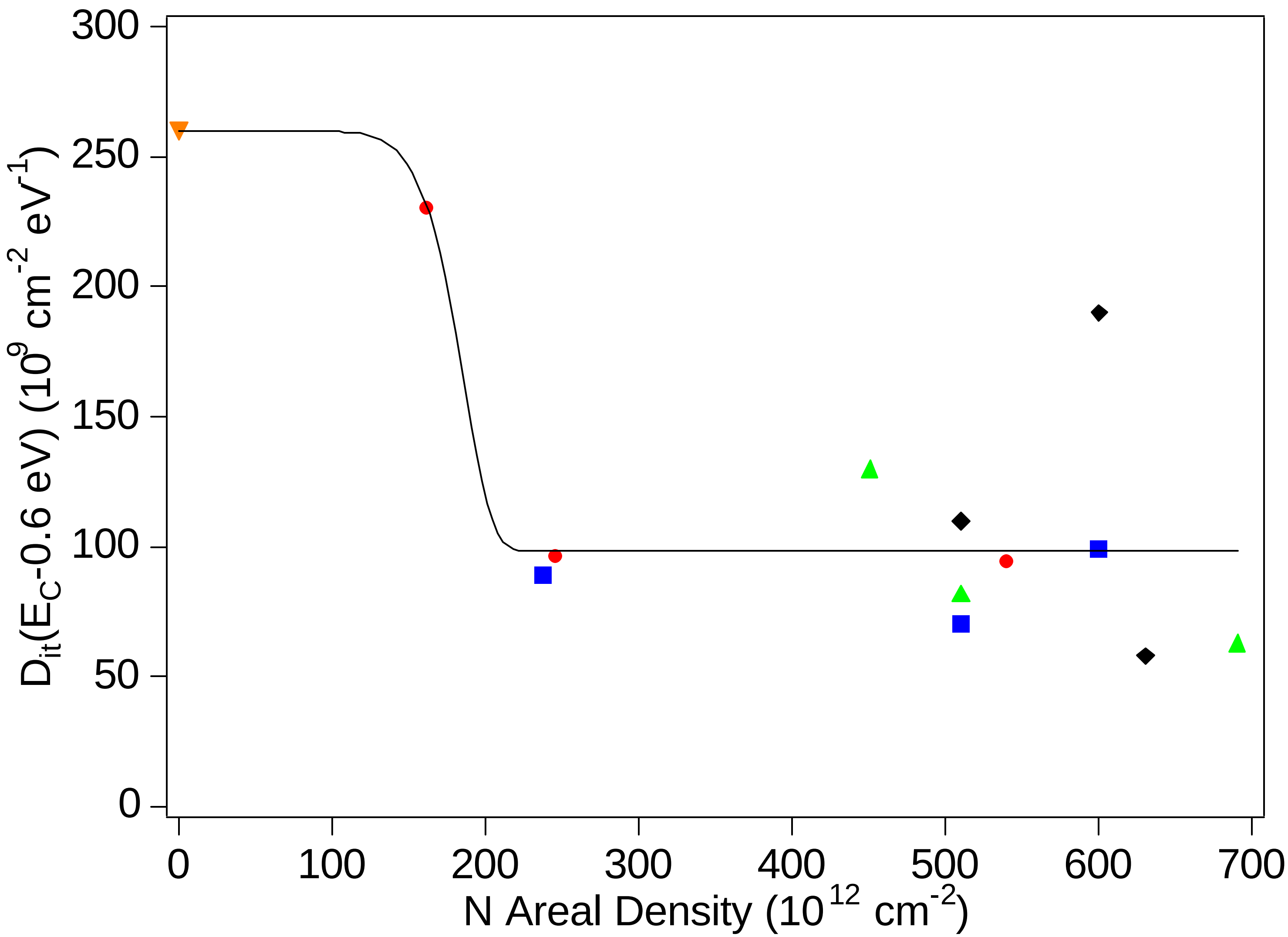
2.5
2.0
1.5
1.0
0.5
0.0
D_it(E_C-0.3 eV) (10^12 cm^-2 eV^-1)
0
100
200
300
400
500
600
700
N Areal Density (10^12 cm^-2)



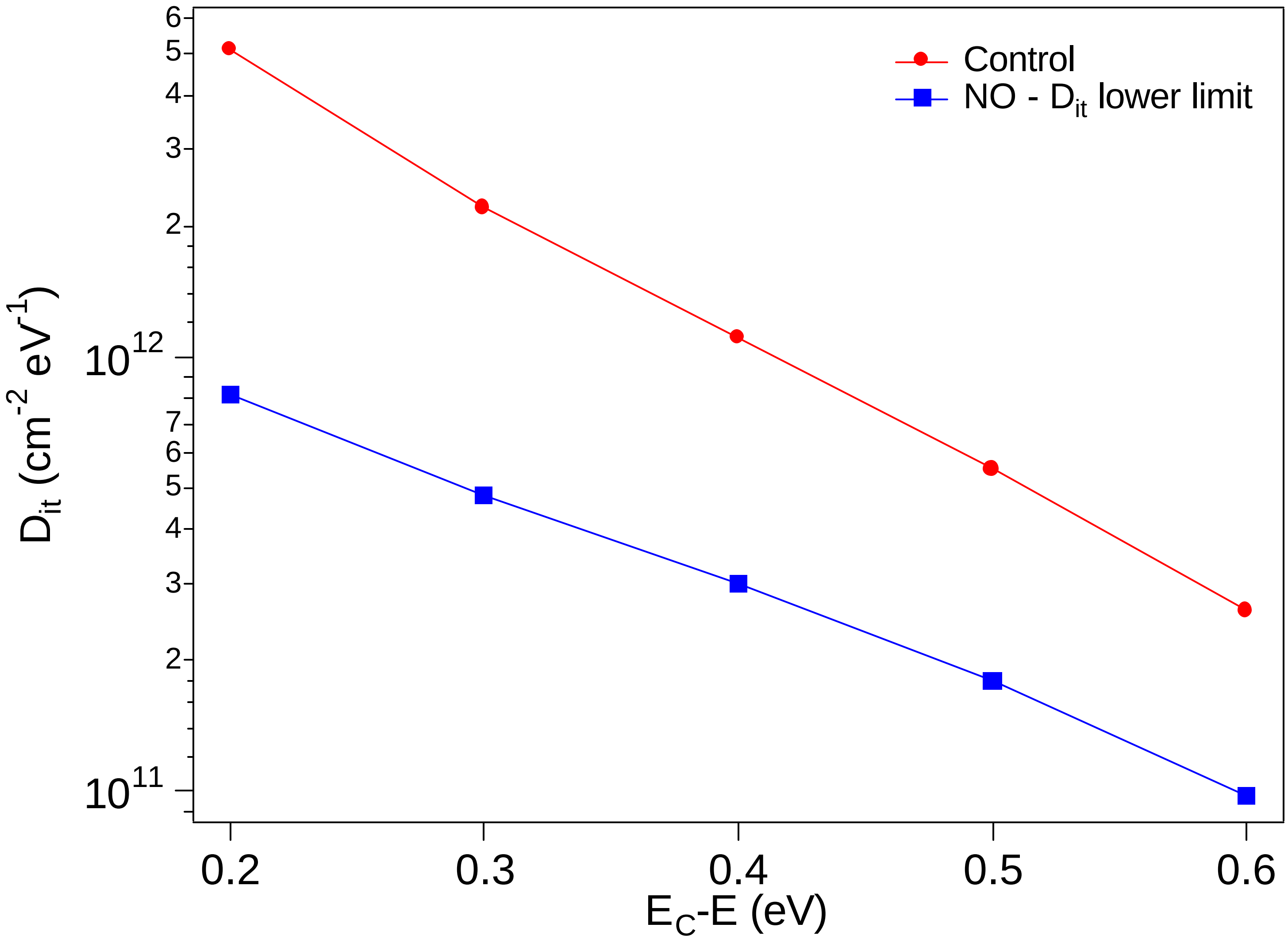
1.2
1.0
0.8
0.6
0.4
0.2
0.0
D_it(E_C-0.4 eV) (10^12 cm^-2 eV^-1)
0
100
200
300
400
500
600
700
N Areal Density (10^12 cm^-2)



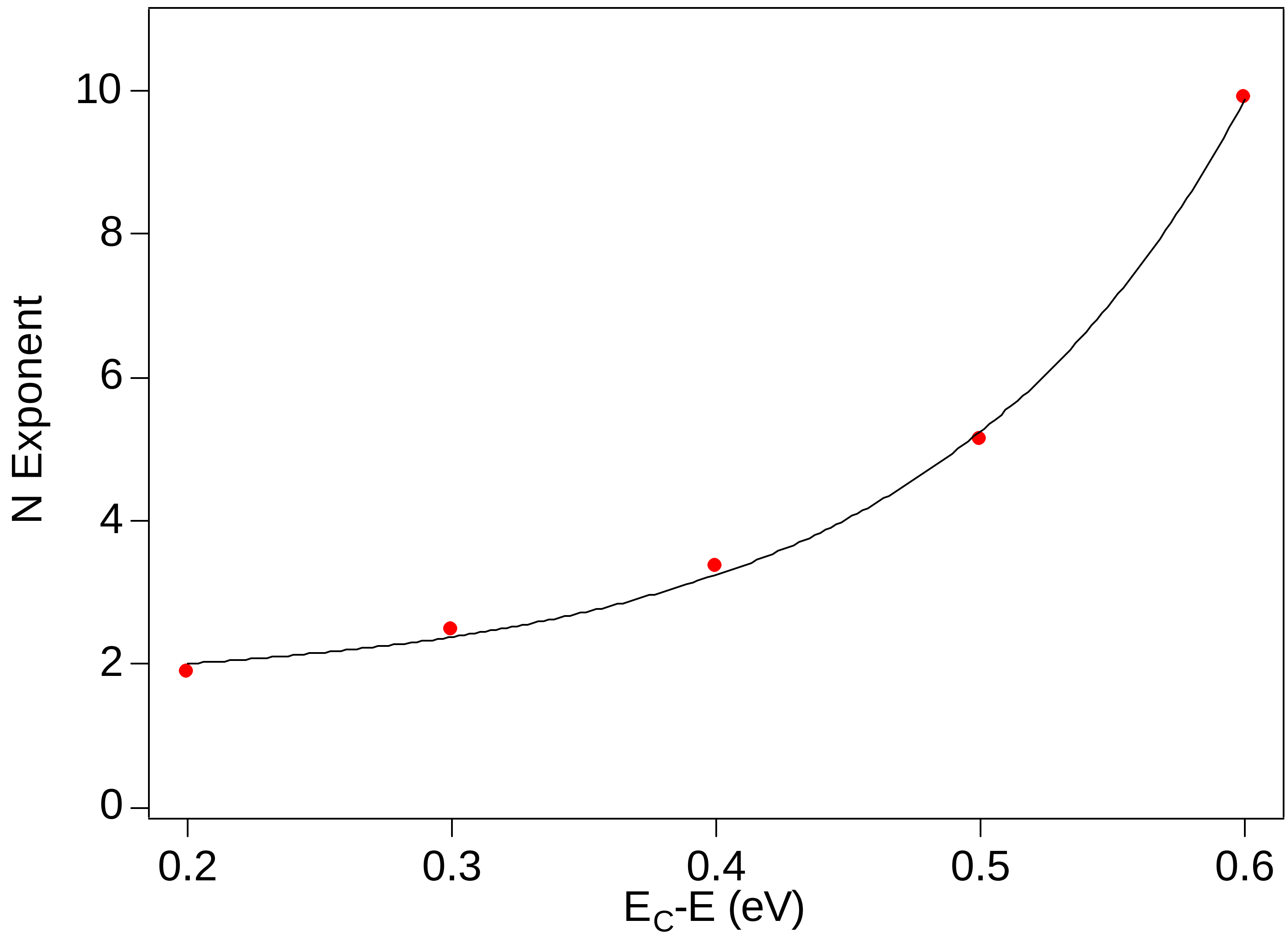
$D_{it}(E_C$-0.5 eV) (10^9 cm^{-2} eV^{-1})
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
N Areal Density (10^{12} cm^{-2})



300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
N Areal Density (10^{12} cm^{-2})
$D_{it}(E_C$-0.6 eV) (10^9 cm^{-2} eV^{-1})



Control
NO - D$_{it}$ lower limit
D$_{it}$ (cm^{-2} eV^{-1})
E$_C$-E (eV)
6
5
4
3
2
10^{12}
7
6
5
4
3
2
10^{11}
0.2
0.3
0.4
0.5
0.6



N Exponent
0
2
4
6
8
10
0.2
0.3
0.4
0.5
0.6
E_C-E (eV)