Relationship between defects induced by irradiation and reduction of hole concentration in Al-doped 4H-SiC

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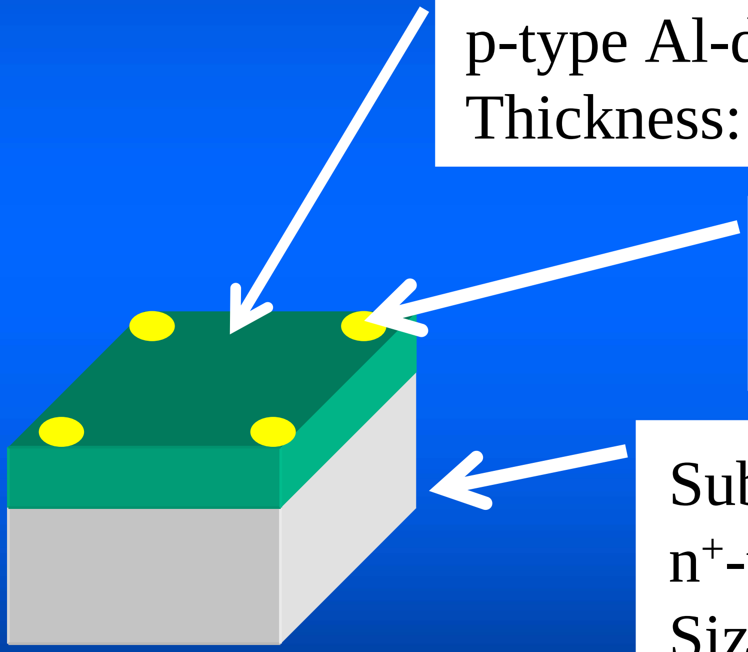
Background of our study

Investigation of acceptors and defects in Al-doped 4H-SiC from p(T) obtained by Hall-effect measurements

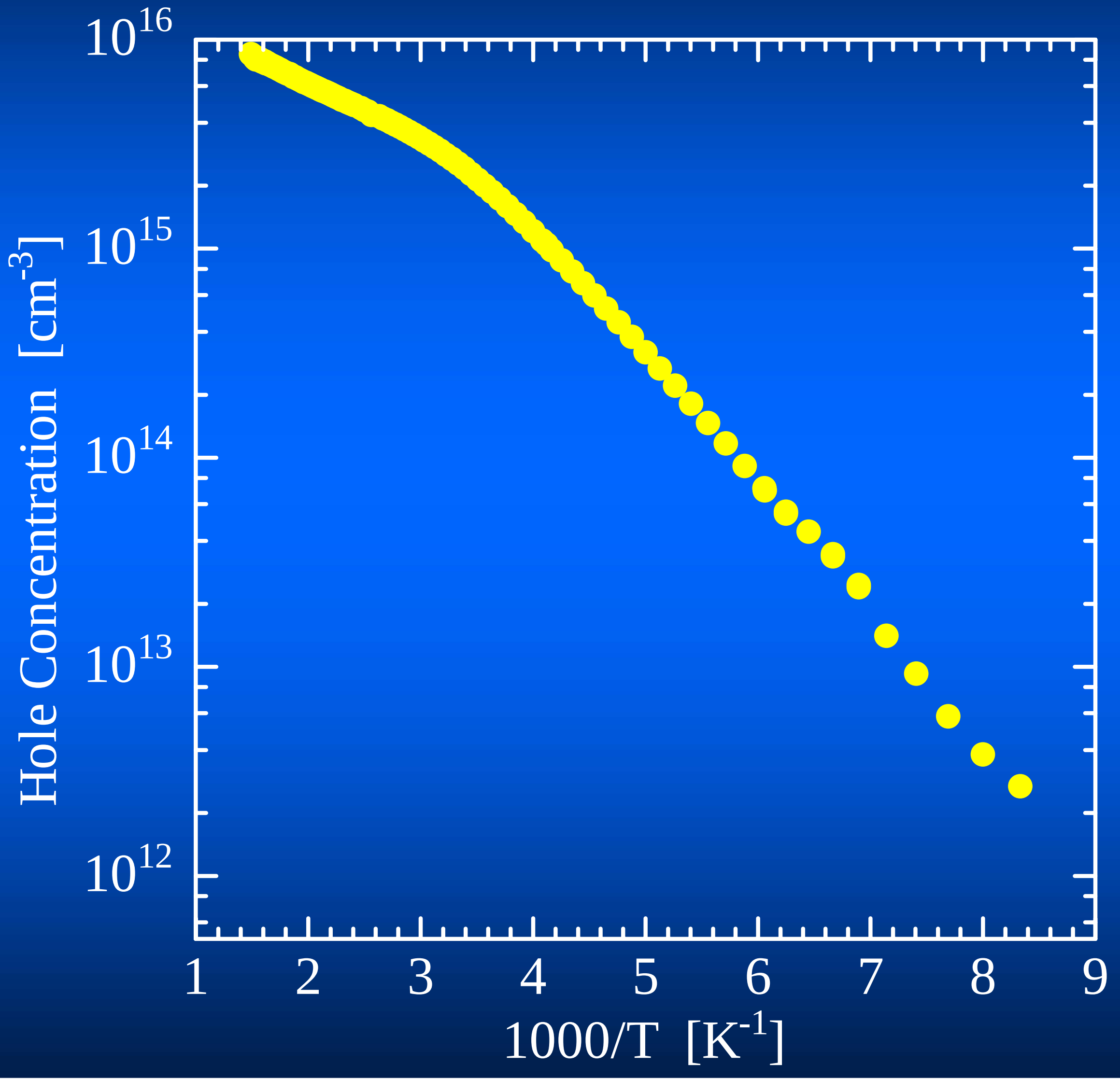


p-type Al-doped 4H-SiC epilayer
Thickness: 10 um

Ohmic contact
Ti/Al

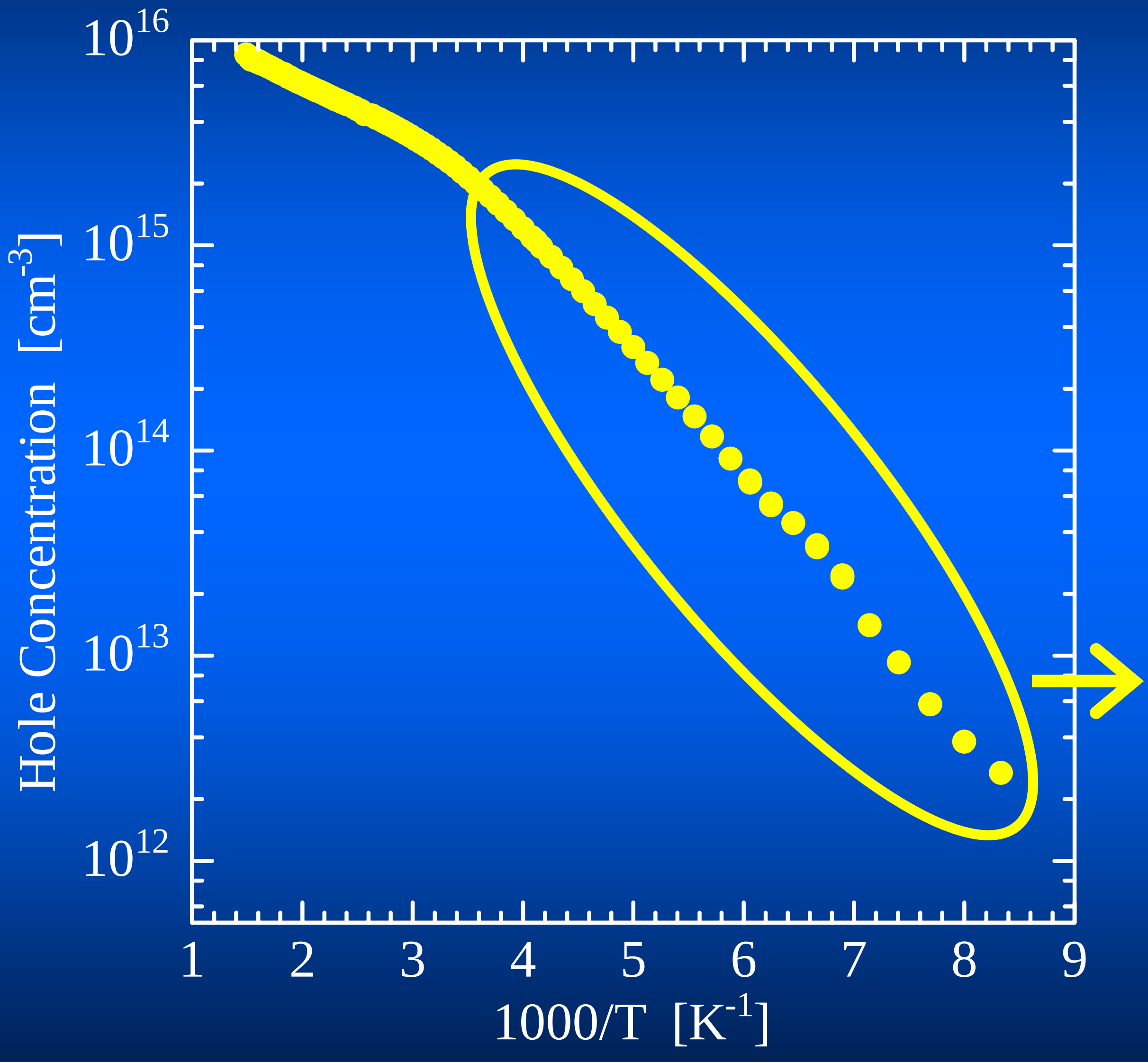
Substrate
n^+-type 4H-SiC wafer
Size: 1x1 cm^2
Thickness: 376 um
Resistivity: 0.02 Ohm cm

Temperature dependence of hole concentration



Lightly Al-doped
4H-SiC epilayer

Temperature dependence of hole concentration

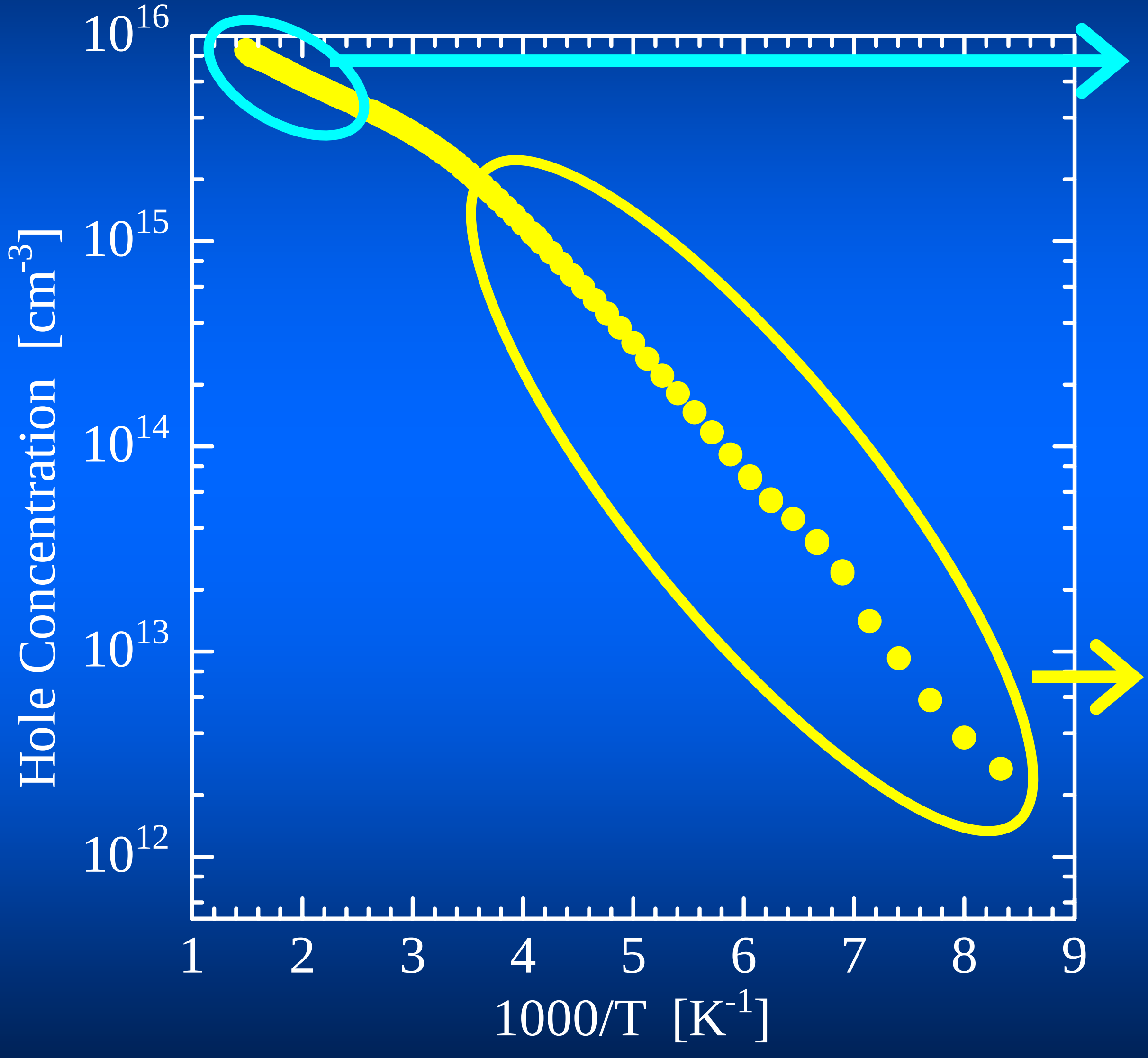


→ **acceptor**

(E_V+200 meV)

Al acceptor

Temperature dependence of hole concentration



deep defect
(E_V+350 meV)
defect-related
acceptor

↓

Unknown

acceptor
(E_V+200 meV)

↓

Al acceptor

Free Carrier Concentration Spectroscopy (FCCS)

$$H(T,E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right)$$

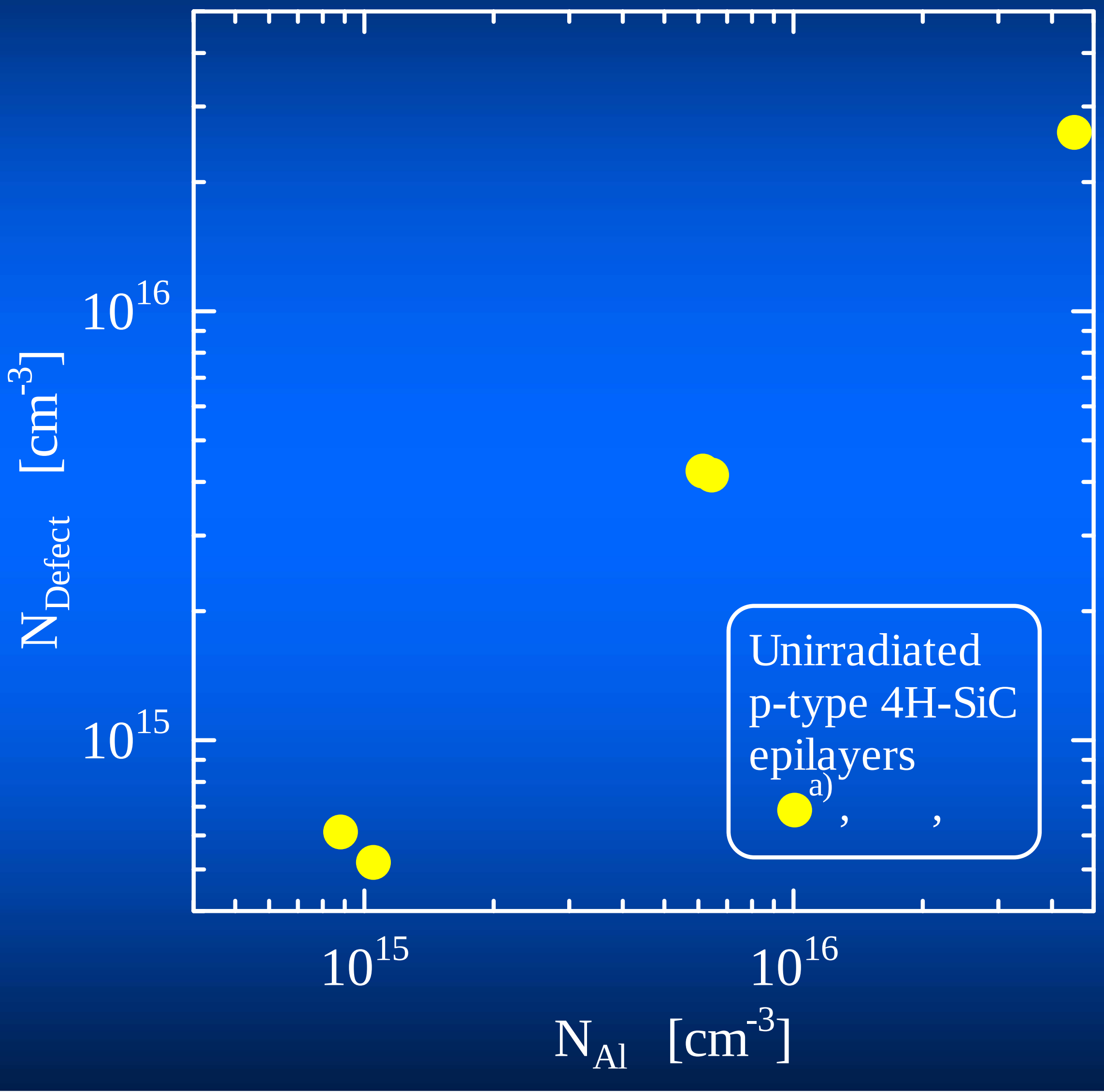
The FCCS signal has a peak at the temperature corresponding to each acceptor level or defect level.

$$\Delta E_i \cong kT_{\mathrm{peak}i} + E_{\mathrm{ref}}$$

$$N_i \cong kT_{\mathrm{peak}i} H(T_{\mathrm{peak}\,i}, E_{\mathrm{ref}}) \exp(-1)$$

In order to verify them, the p(T) simulated with the densities and energy levels determined by FCCS is always compared with the experimental p(T).

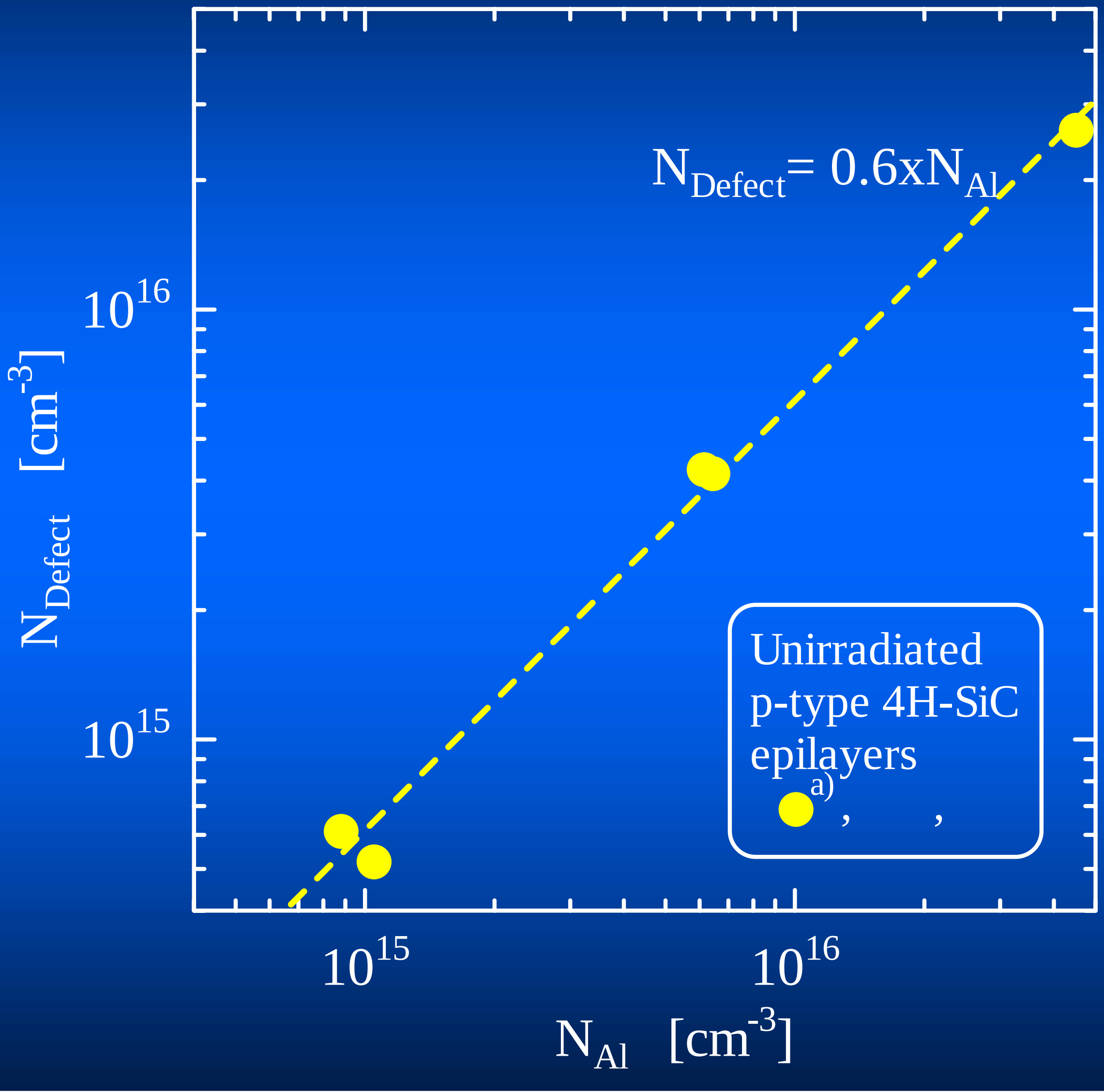
Relationship between N_{Al} and N_{Defect}



N_{Al}:
Al acceptor density

N_{Defect}:
Deep defect density

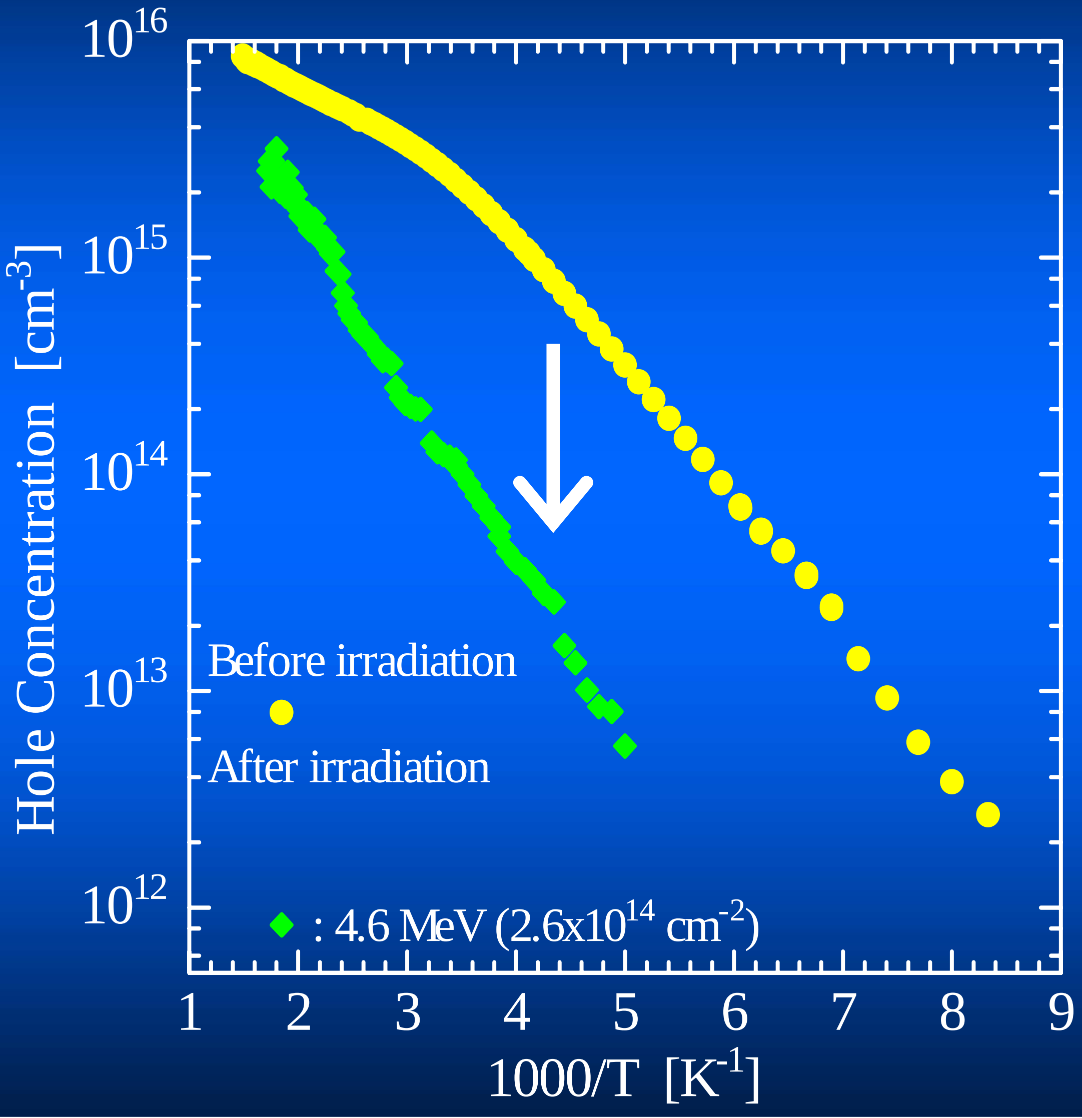
Relationship between N_{Al} and N_{Defect}



$$N_{Defect} = 0.6 \text{ x } N_{Al}$$

The unknown deep defect is most likely related to Al

With irradiation of 4.6 MeV electrons



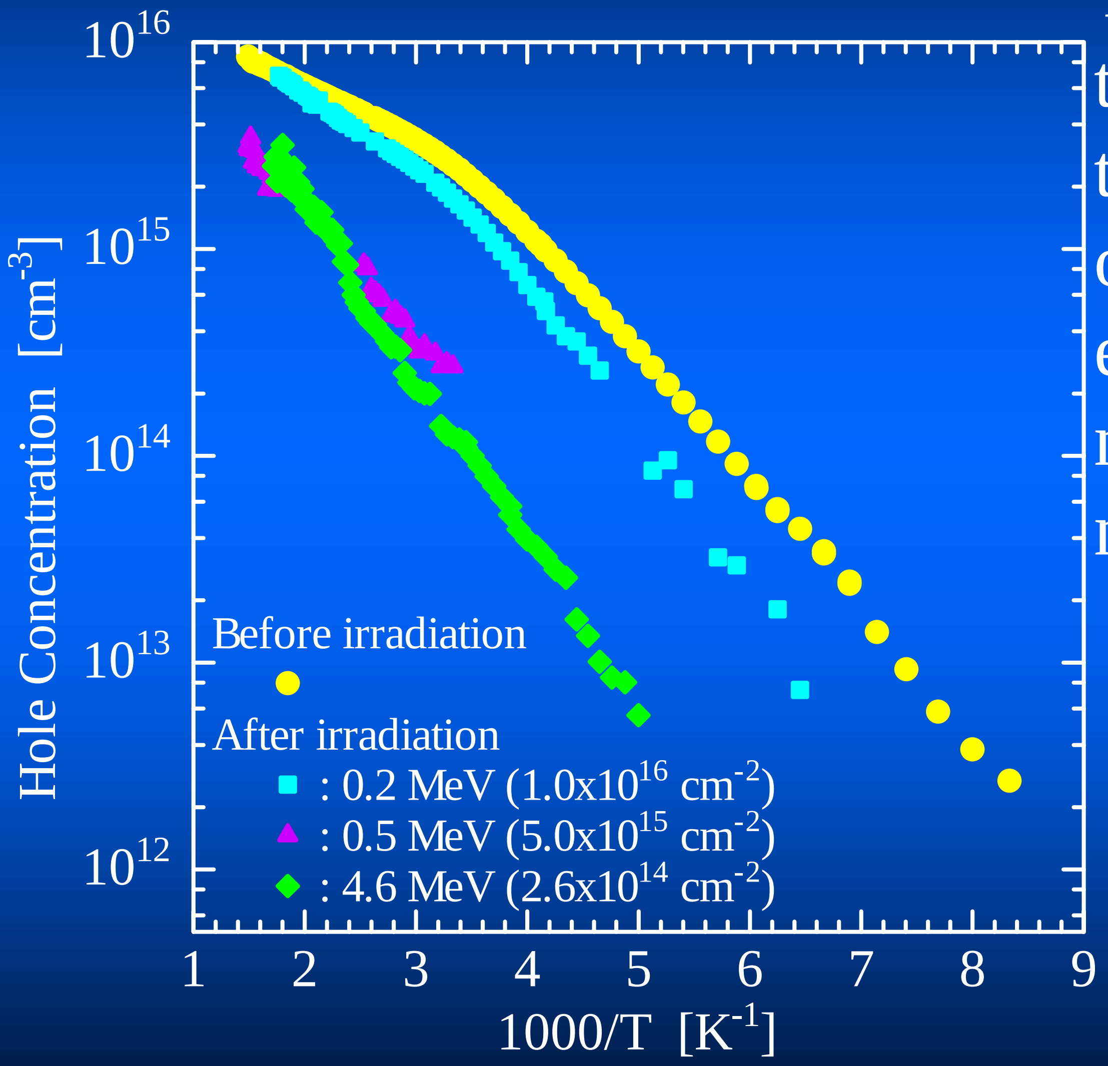
Although the fluence of 4.6 MeV electrons is very small (2.6×10^{14} cm^{-2}),

the p(T) is reduced significantly by irradiation

Motivation of our study

1. **What is the origin of the deep defect?**
2. **Why was the p(T) reduced by irradiation?**

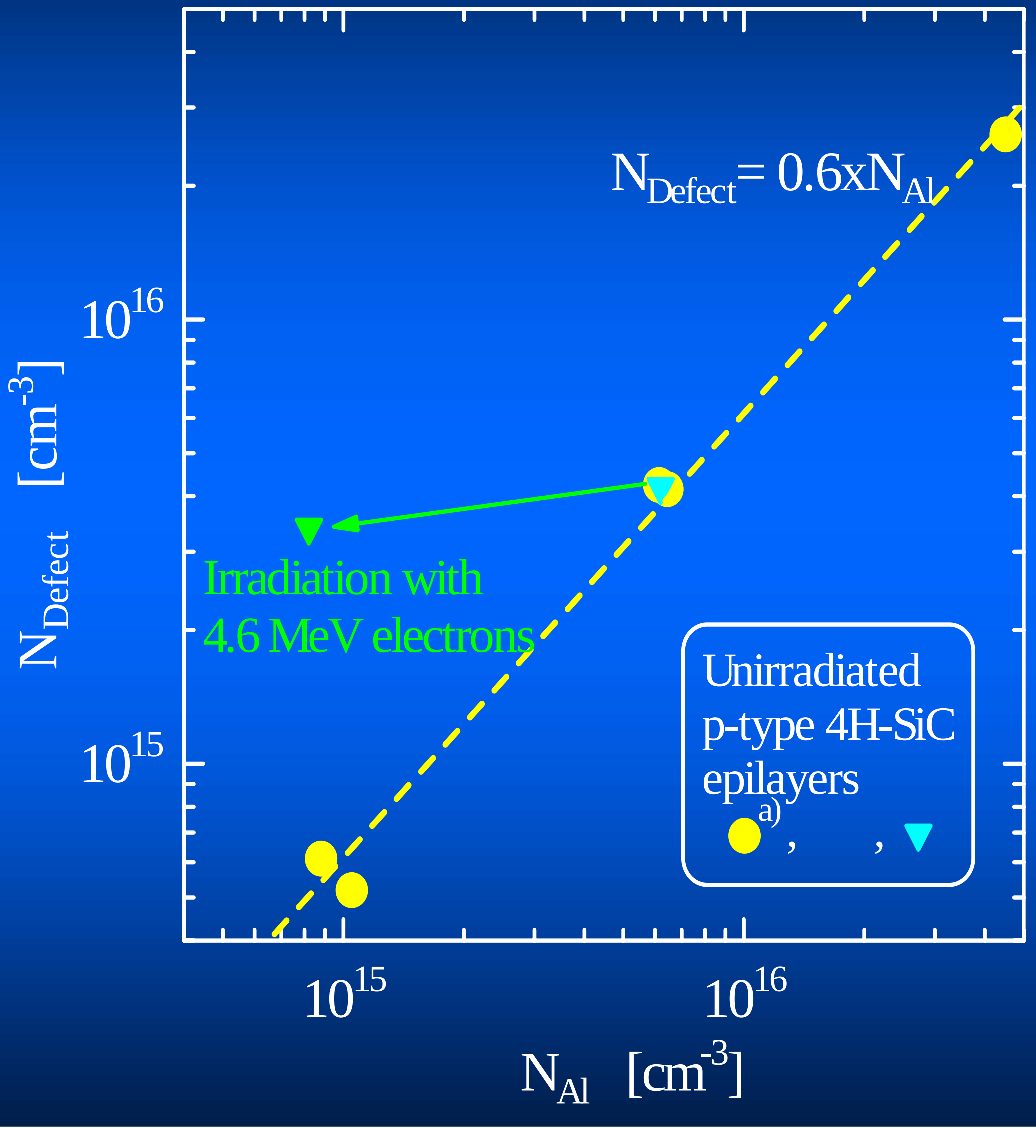
Irradiation of electrons with several energies



The hole concentration for the sample irradiated with the **1.0×10^{16} cm^{-2}** fluence of **0.5 MeV or 1 MeV** electrons could not be measured because of much higher resistivity.

Reduction in p(T) is quite different between 0.2 MeV and >0.5 MeV electron irradiations.

With irradiation of 4.6 MeV electrons

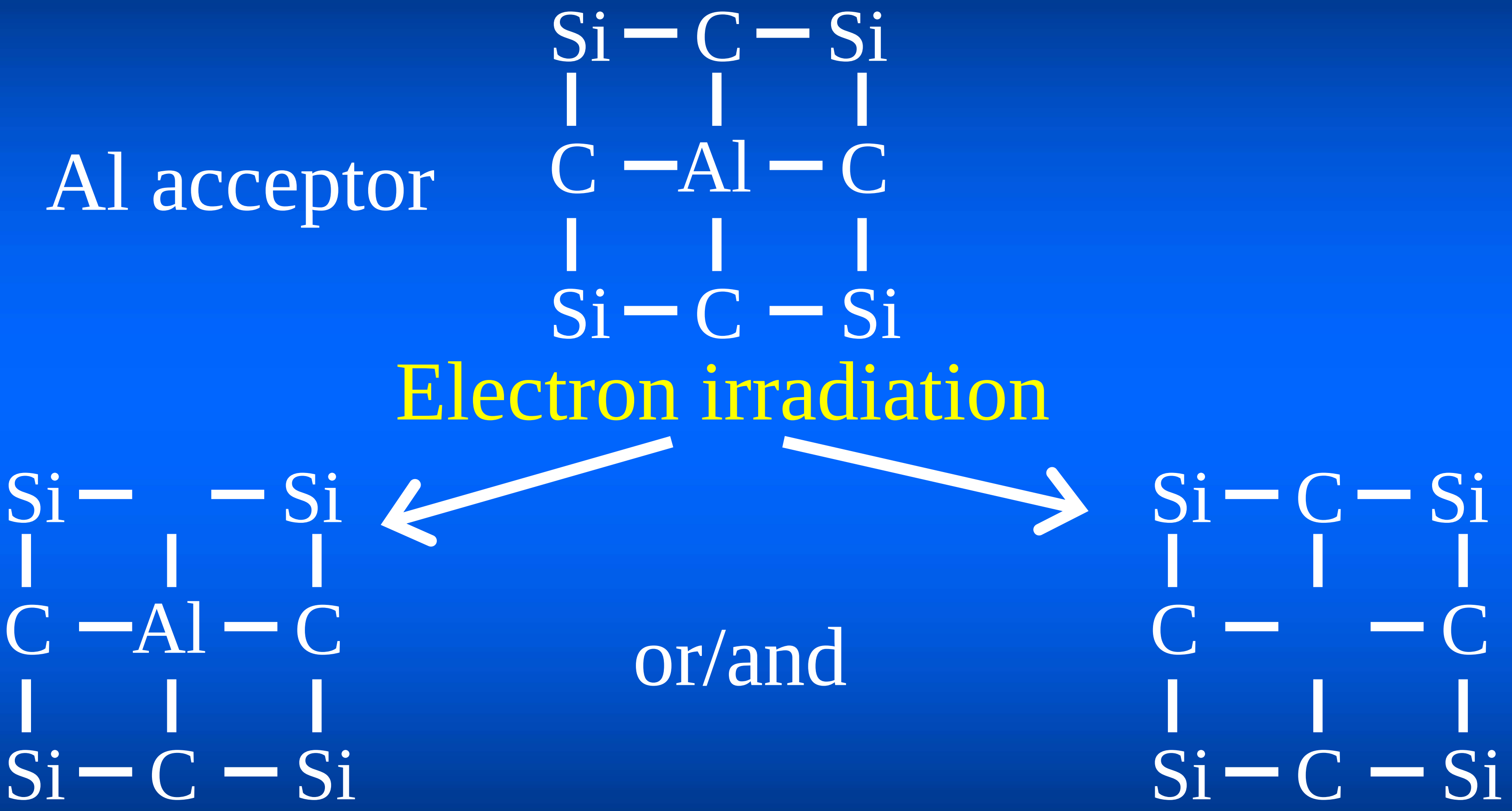


The N_{Al} is decreased significantly

↕

The N_{Defect} is decreased slightly

The reason why the N_{Al} is reduced by irradiation



Al acceptor

Si — C — Si
| | |
C — Al — C
| | |
Si — C — Si

Electron irradiation

Si — — Si
| | |
C — Al — C
| | |
Si — C — Si

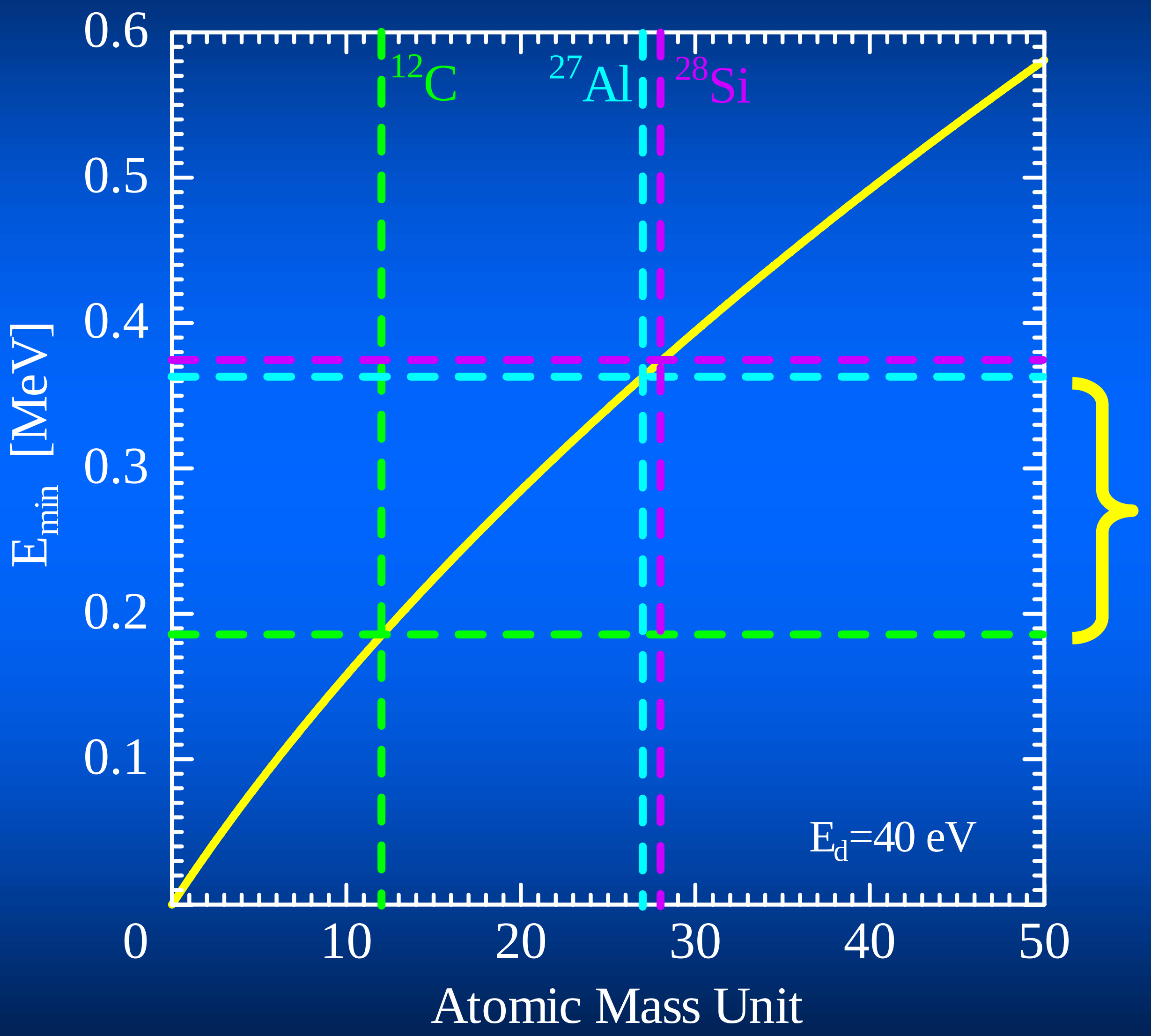
or/and

Si — C — Si
| | |
C — — C
| | |
Si — C — Si

Displacement of C

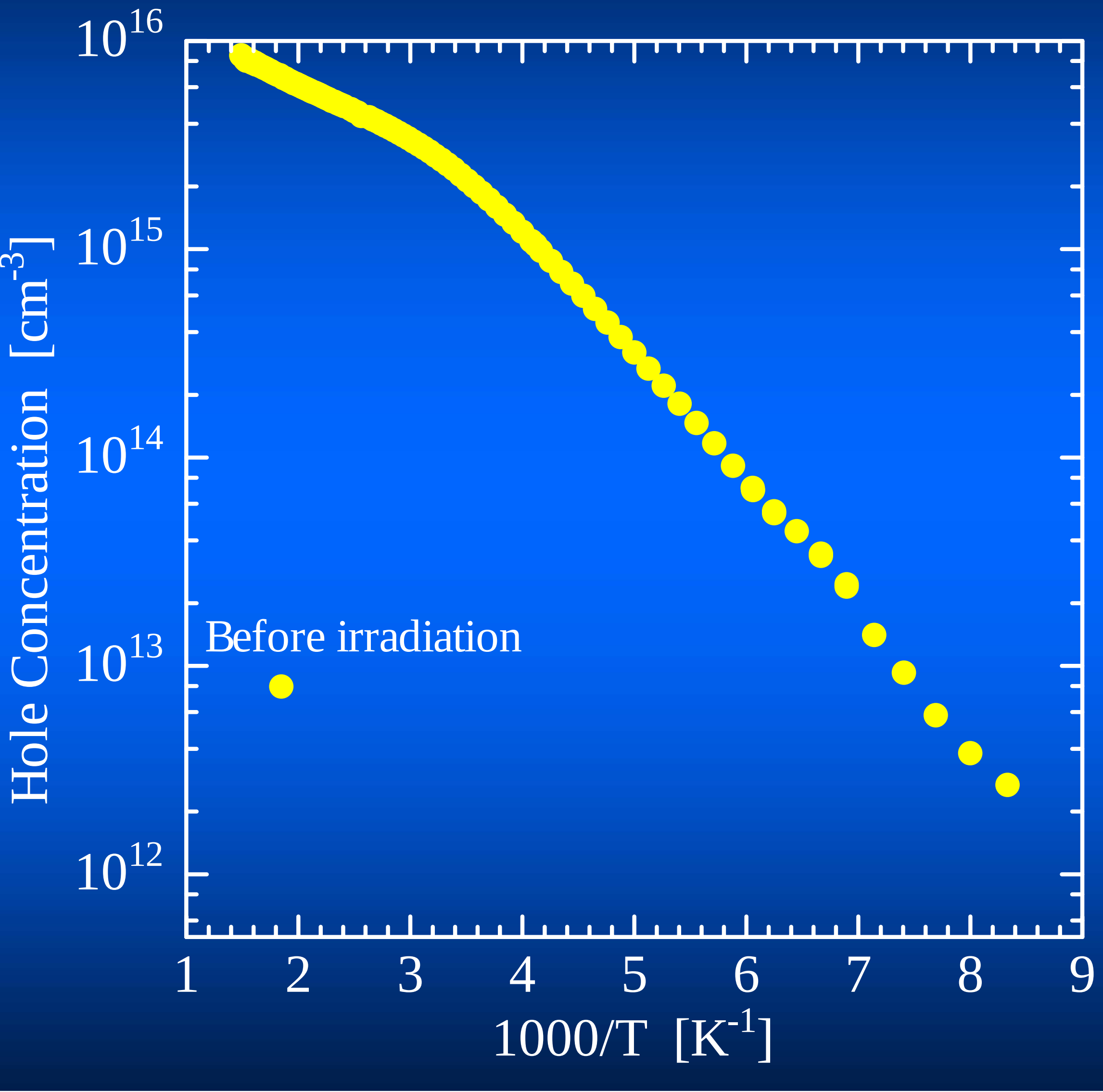
Displacement of Al

Minimum electron energy required for displacement of atom

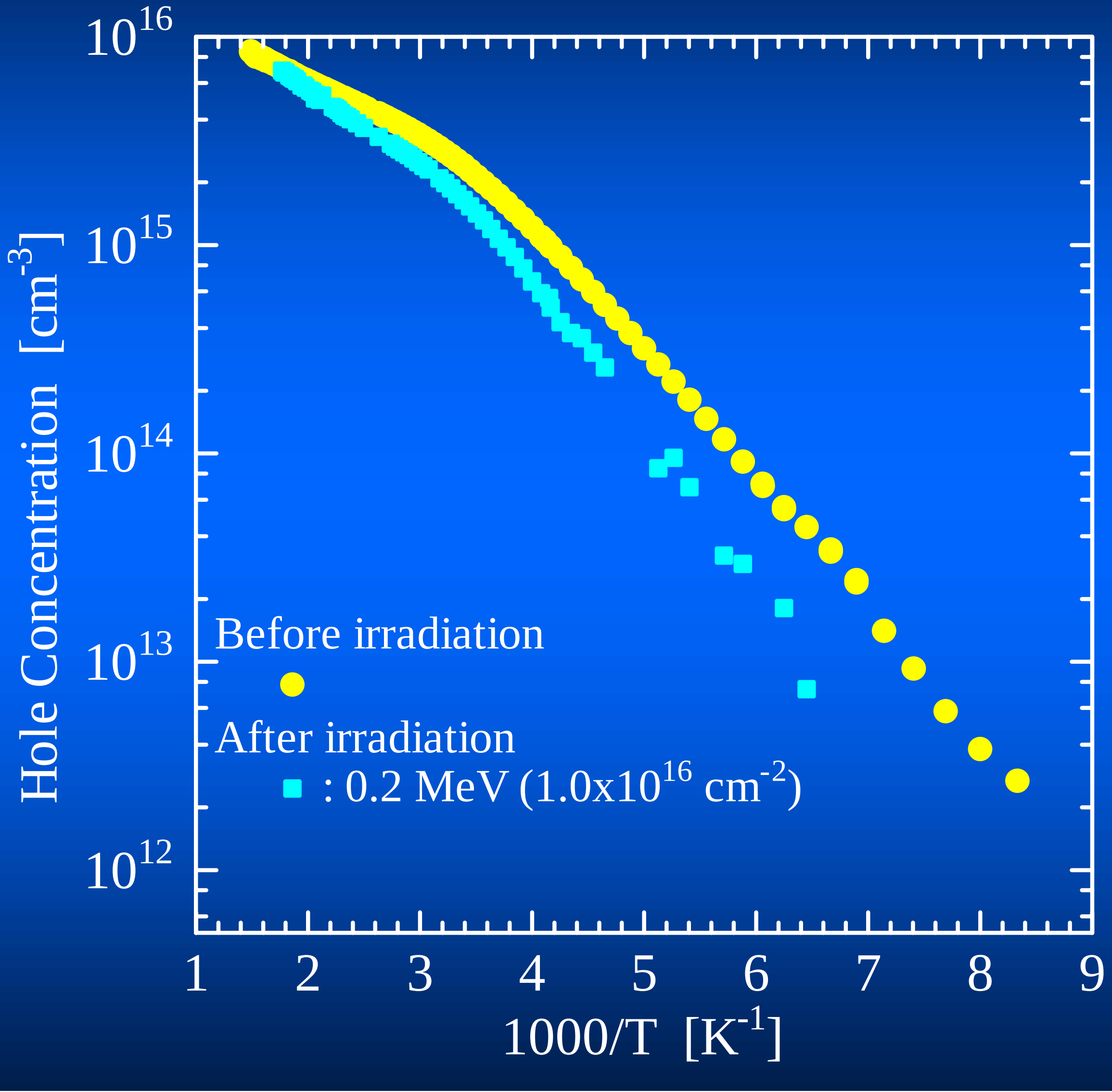


Electrons with 0.19-0.36 MeV can displace only C atoms

Before irradiation

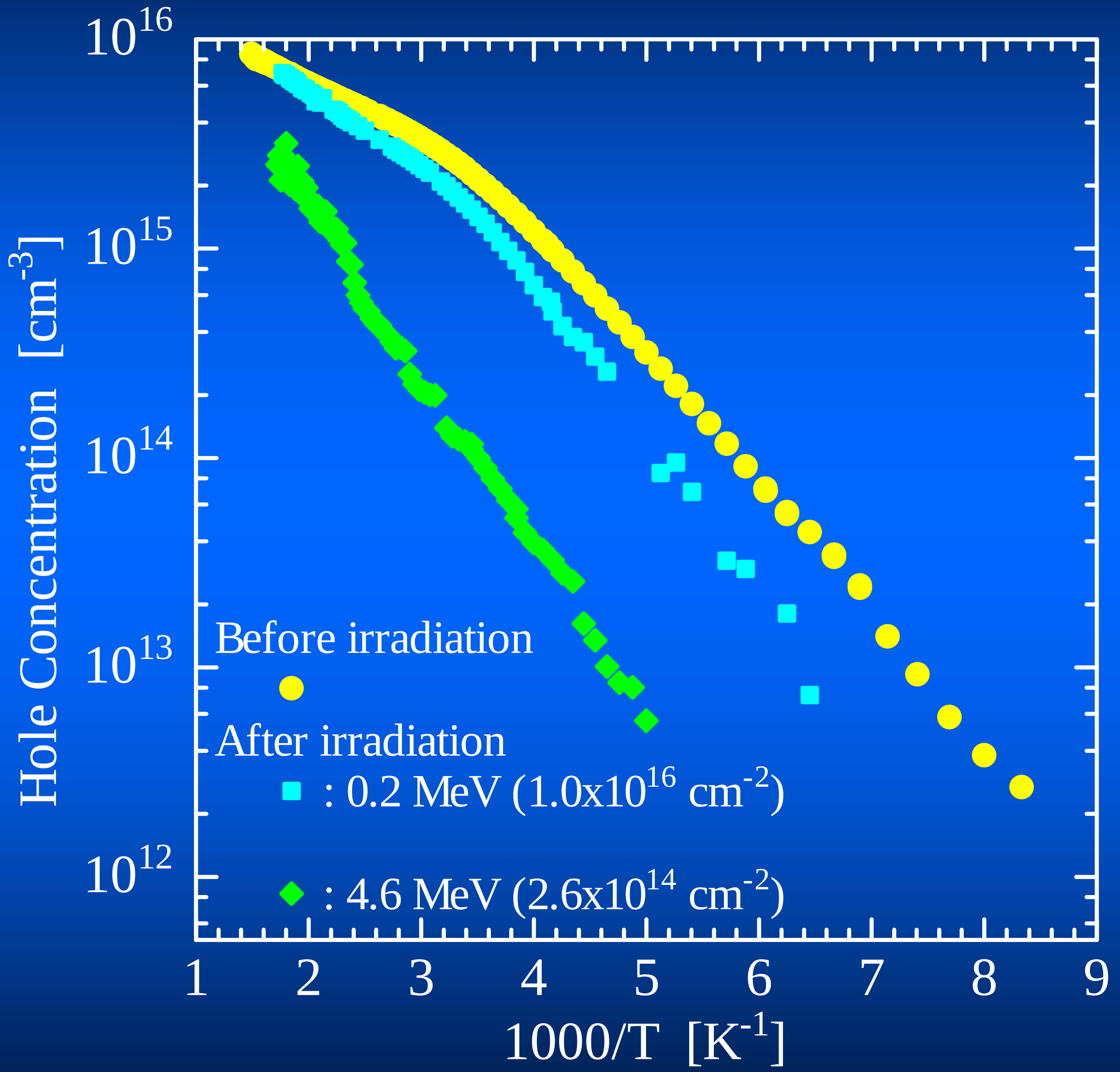


With irradiation of 0.2 MeV electrons



0.2 MeV electrons
at 1.0×10^{16} cm^{-2}

With irradiation of 0.2 MeV and 4.6 MeV electrons



0.2 MeV electrons
at 1.0x10^{16} cm^{-2}

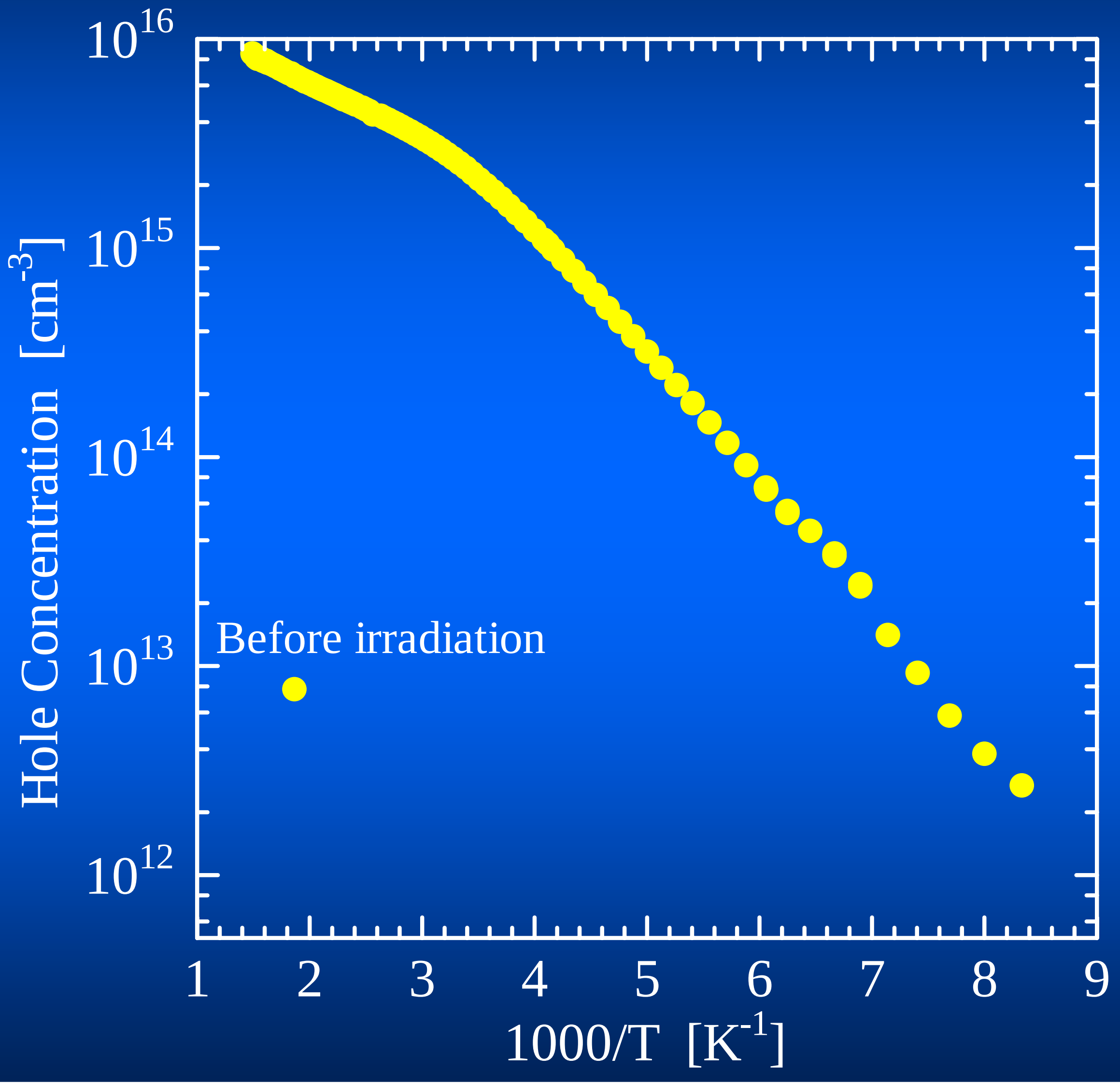
Low energy

High fluence

4.6 MeV electrons
at 2.6x10^{14} cm^{-2}

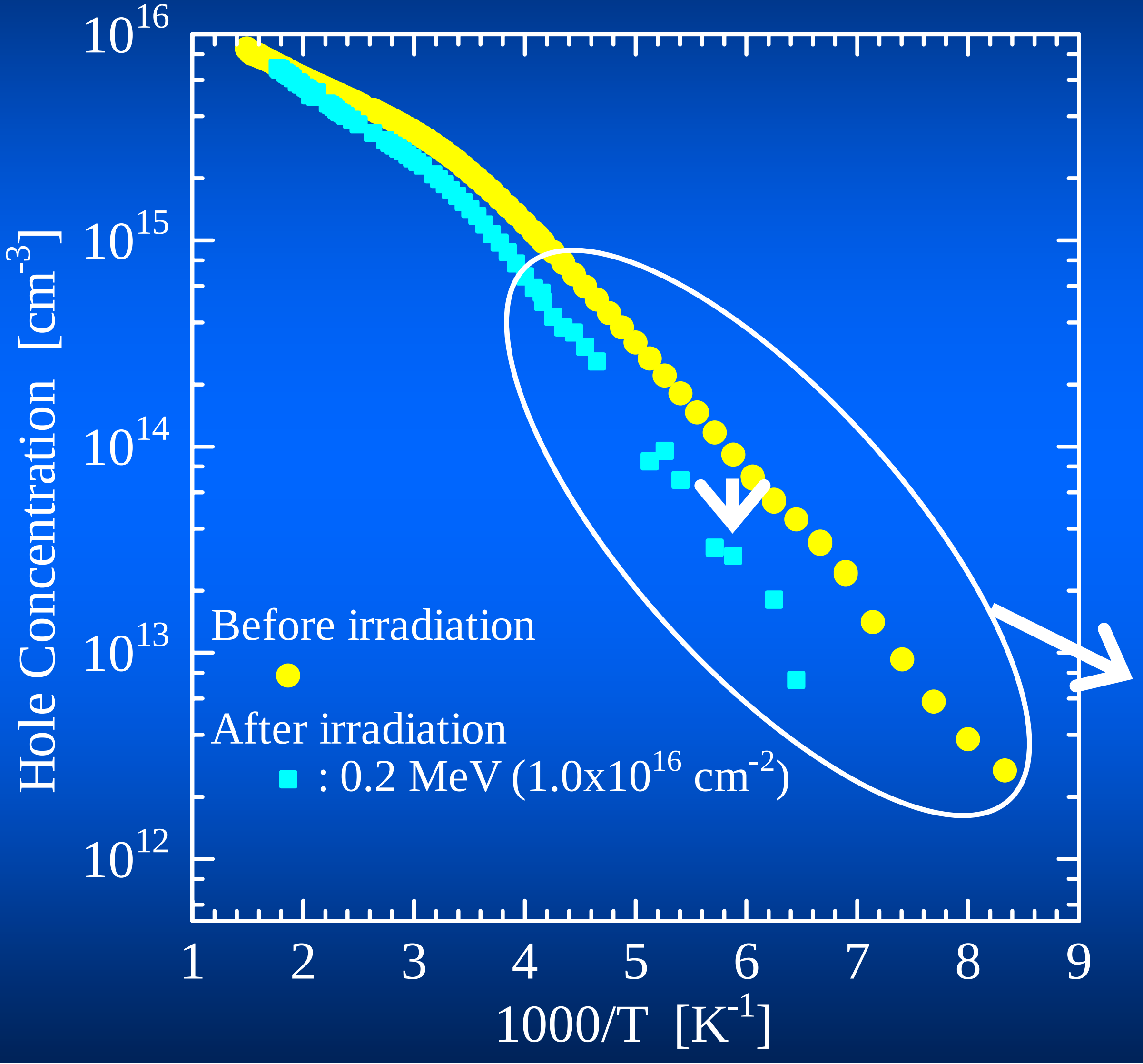
The p(T) is reduced slightly with 0.2 MeV electrons

Before irradiation of 0.2 MeV electrons



Al-doped 4H-SiC epilayer

With irradiation of 0.2 MeV electrons

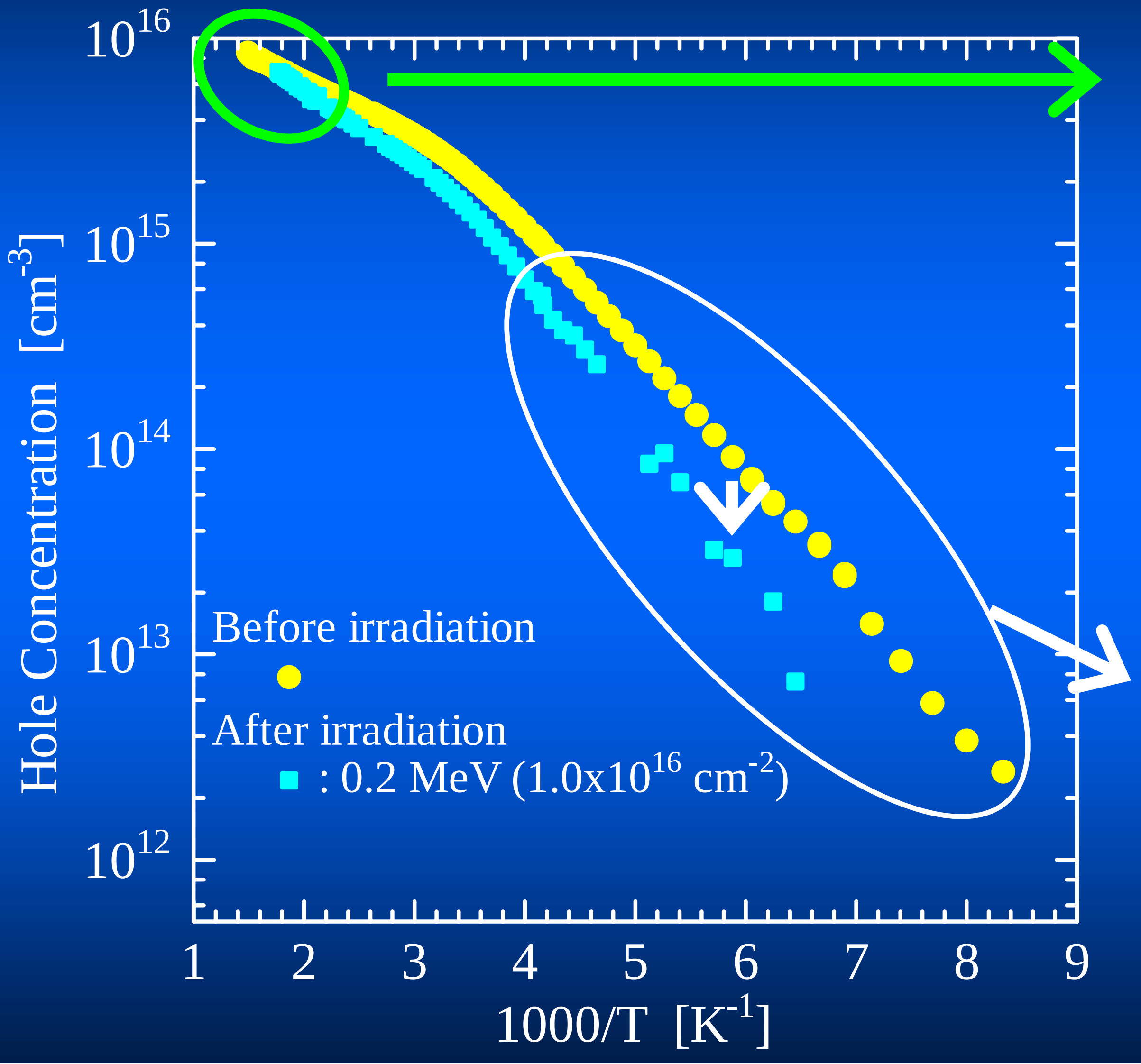


At low temperatures p(T) is reduced

⬇

N_{Al} is decreased

With irradiation of 0.2 MeV electrons



At high temperatures p(T) is unchanged

↓

$N_{Al} + N_{Defect}$ may be unchanged

At low temperatures p(T) is reduced

↓

N_{Al} is decreased

Results from p(T) by FCCS

		Before irradiation	0.2 MeV	4.6 MeV
ΔE_{Al}	[meV]	203 (203)	217	206
N_{Al}	[x10^{15} cm^{-3}]	5.2 (6.2)	4.3	0.82
$\Delta E_{\mathrm{Defect}}$	[meV]	357 (365)	363	383
N_{Defect}	[x10^{15} cm^{-3}]	3.5 (4.2)	5.2	3.5
N_{comp}	**[x10^{15} cm^{-3}]**	**0.047 (0.037)**	**0.21**	**0.74**

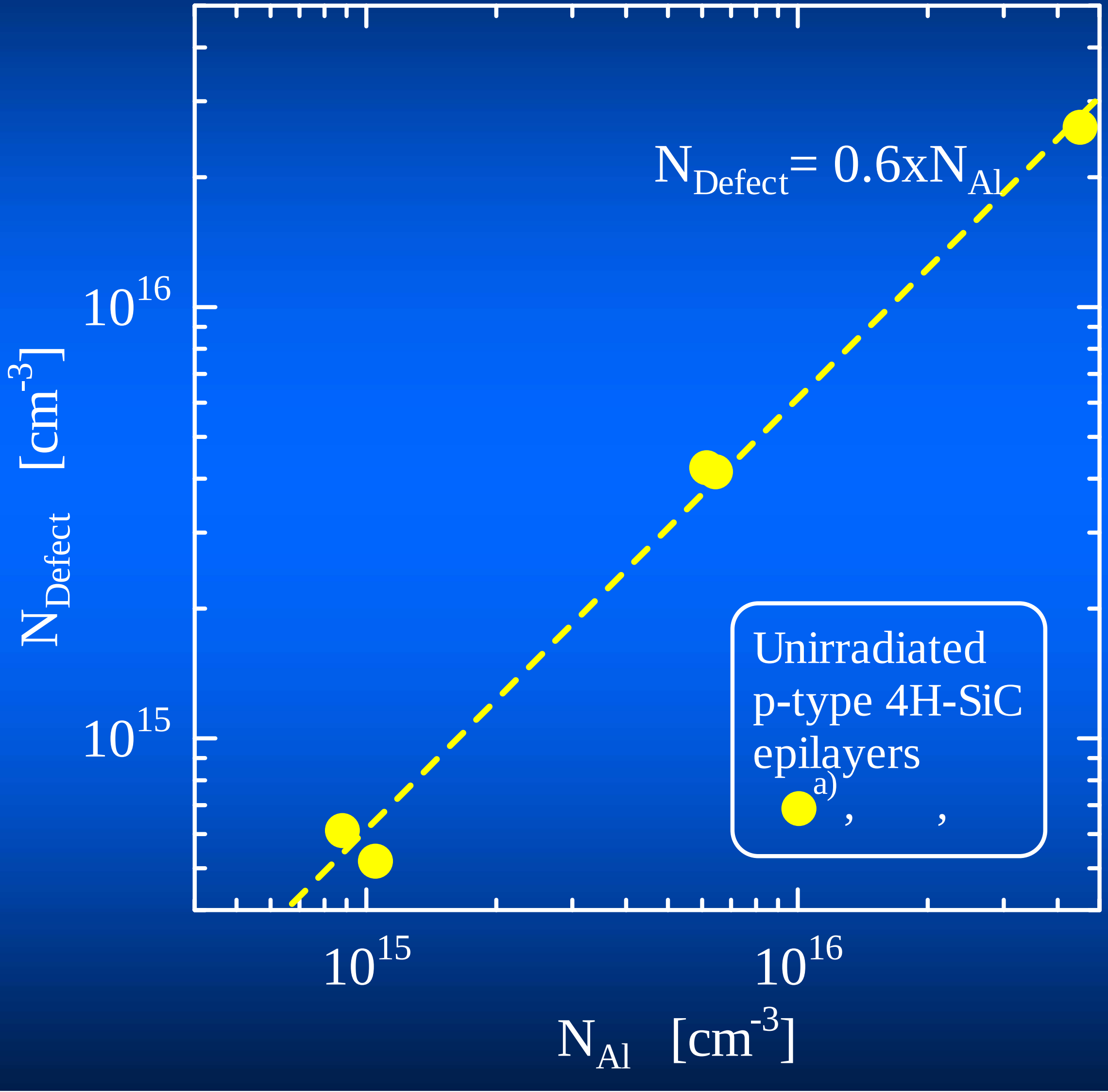
Defect means a defect-related acceptor.

(….) represents data for before 4.6 MeV electron irradiation.

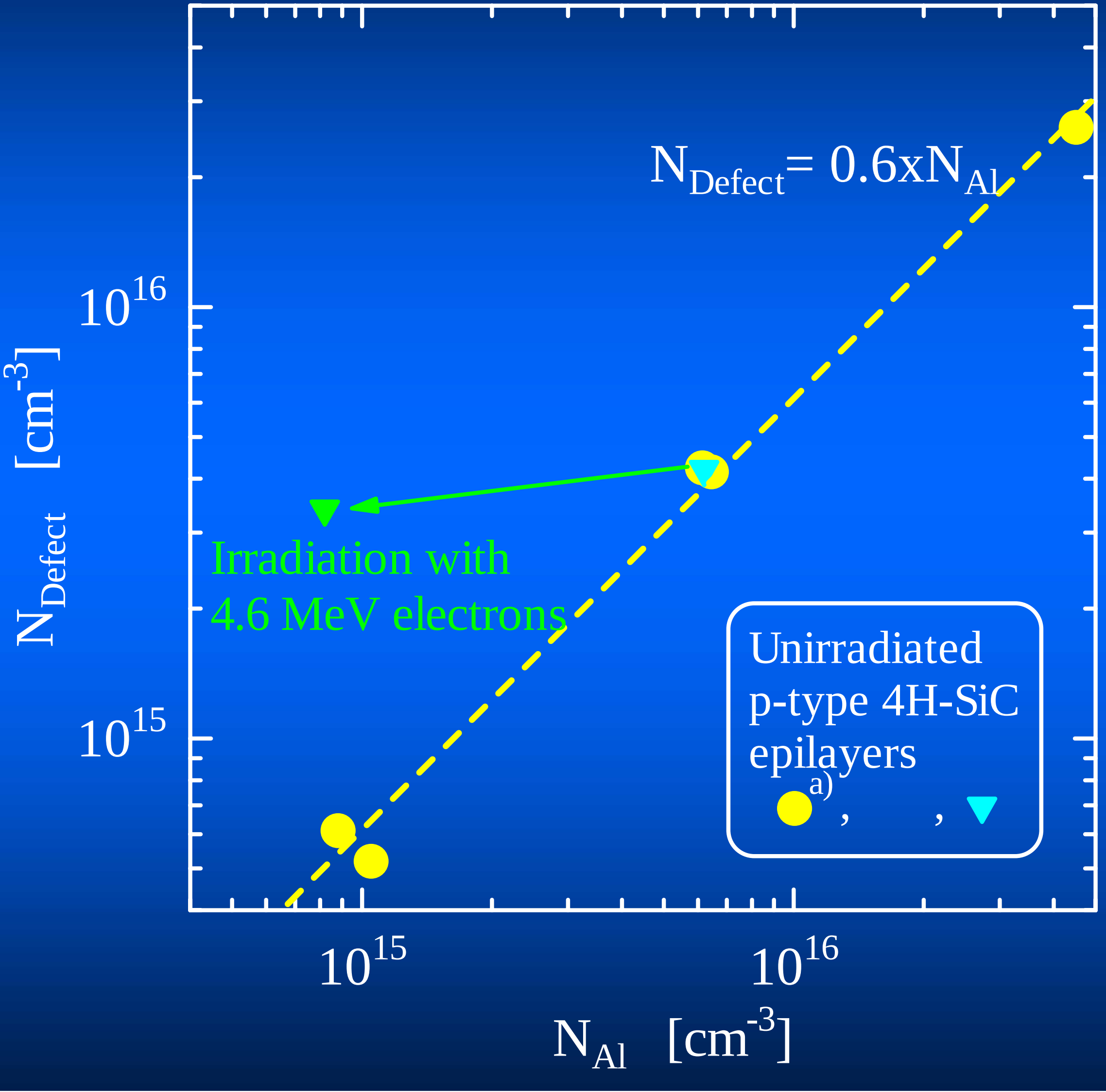
N_{comp} represents the density of hole traps deeper than this defect level and donor-like defect.

The effect of hole traps on p(T) is negligible.

Change of relationship between N_{Al} and N_{defect} by irradiation



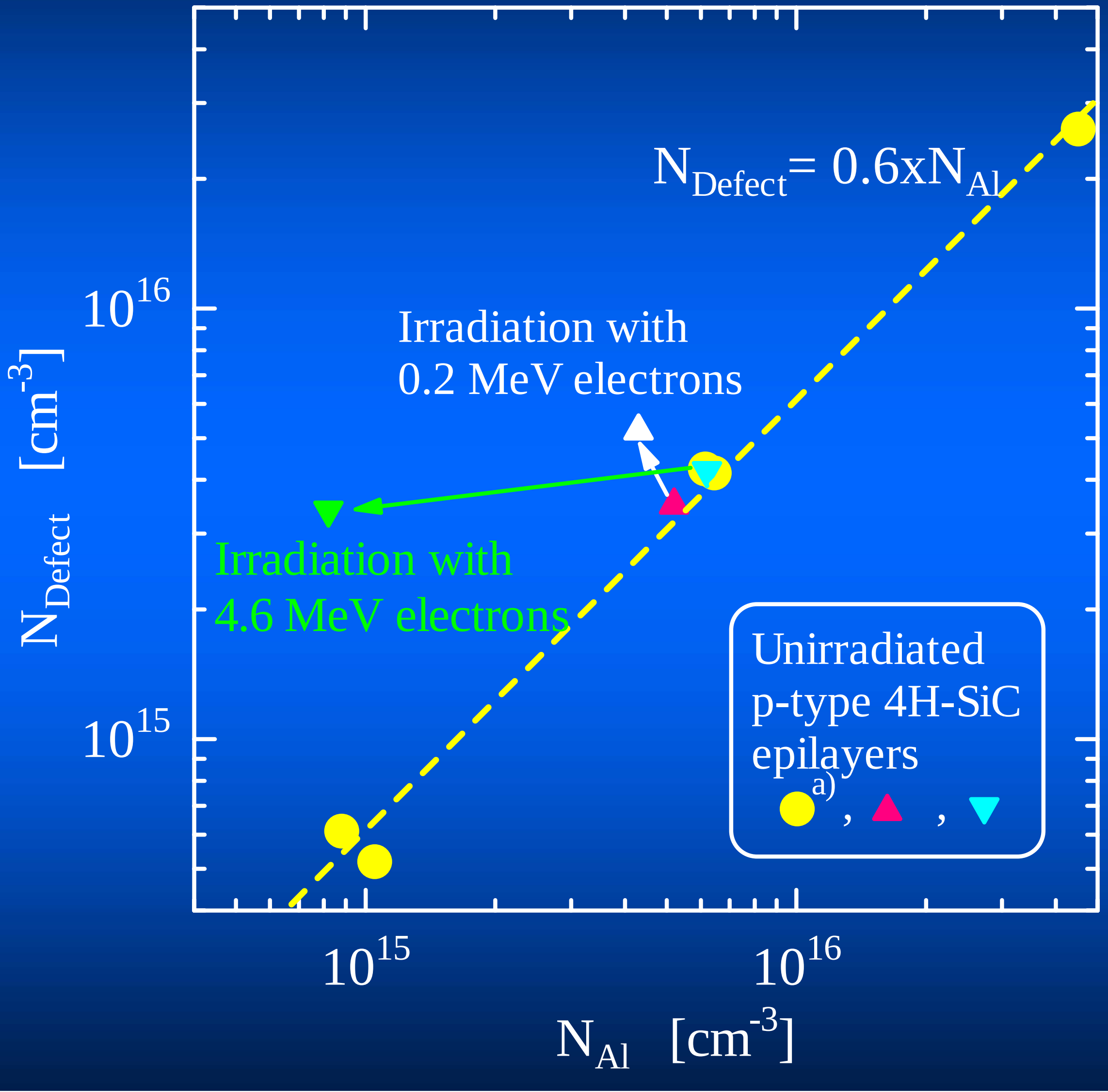
Changes of N_{Al} and N_{defect} by irradiation



With irradiation of 4.6 MeV electrons

1. **N_{Al} is decreased**
2. **N_{Defect} is decreased**

Changes of N_{Al} and N_{defect} by irradiation



With irradiation of 4.6 MeV electrons

⇩

1. **N_{Al} is decreased**
2. **N_{Defect} is decreased**

With irradiation of 0.2 MeV electrons

⇩

1. **N_{Al} is decreased**
2. **N_{Defect} is increased**

With 0.2 MeV electron irradiation

Si — C — Si
C — Al — C
Si — C — Si

C is only displaced

C vacancy is created

Si — — Si
C — Al — C
Si — C — Si

Al_{Si}-V_C is formed

1. Al acceptor density should be decreased

2. Al_{Si}-V_C complex density should be increased

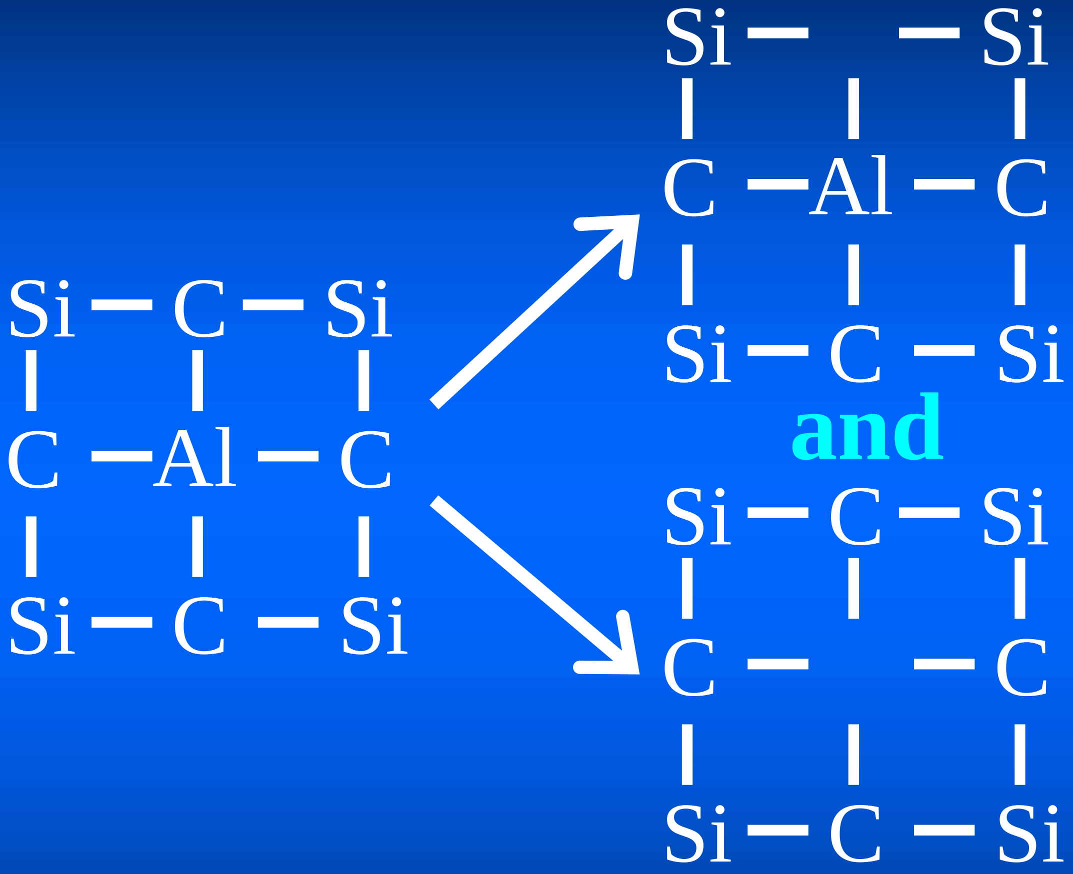
With 0.2 MeV electron irradiation

1. **N_{Al} is decreased from 5.2×10^{15} to 4.3×10^{15} cm^{-3}**
2. **N_{Defect} is increased from 3.5×10^{15} to 5.2×10^{15} cm^{-3}**

The decrement of N_{Al} is nearly equal to the increment of N_{Defect}

The deep defect is most likely Al_{Si}-V_C

With >0.5 MeV electron irradiation



1. N_{Al} is decreased
2. N_{Defect} is increased

1. N_{Al} is decreased
2. N_{Defect} is decreased

1. N_{Al} should be decreased significantly
2. N_{Defect} might be decreased slightly

These are in good agreement with the results

Conclusion

With 0.2 MeV electron irradiation, the Al acceptor density was decreased, while the unknown deep defect density was increased.

Since a 0.2 MeV electron could displace only C into an interstitial site, the Al acceptor density was decreased due to the displacement of its nearest neighbor C, which resulted in an increase in the density of Al_{Si}-V_C complexes.

This suggests that the unknown deep defect in lightly Al-doped 4H-SiC epilayers is the Al_{Si}-V_C complex.

Appendix

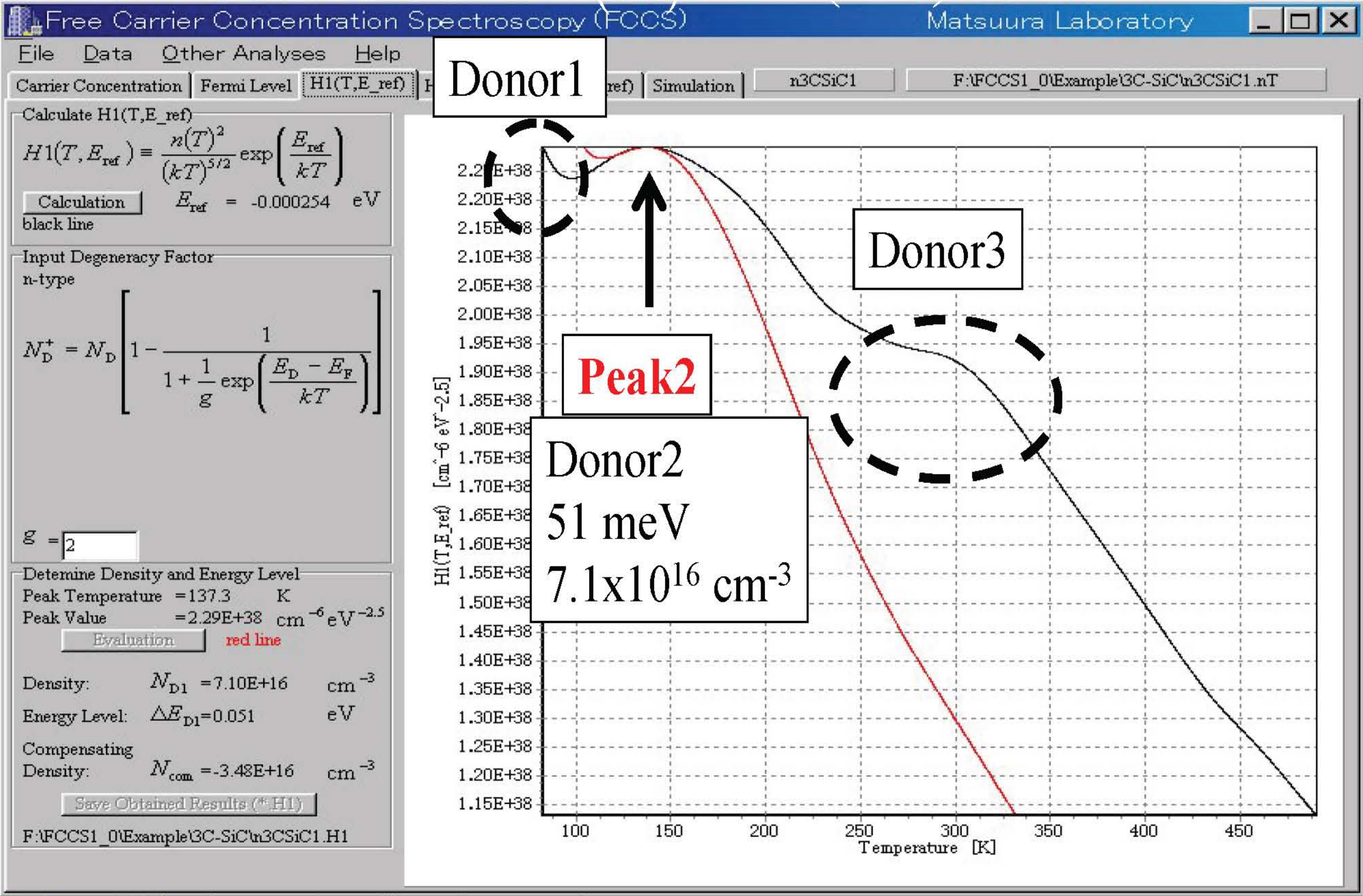
Free Carrier Concentration Spectroscopy (FCCS)

$$H(T, E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right)$$

The FCCS signal has a peak corresponding to each acceptor level or defect level.

$$\Delta E_i \cong kT_{\mathrm{peak}i} + E_{\mathrm{ref}}$$

$$N_i \cong kT_{\mathrm{peak}i} H(T_{\mathrm{peak}\,i}, E_{\mathrm{ref}}) \exp(-1)$$



Calculate H1(T,E_ref)

$$H1(T,E_{\rm ref}) = \frac{n(T)^2}{(kT)^{5/2}}\exp\left(\frac{E_{\rm ref}}{kT}\right)$$

$E_{\rm ref}$ = -0.000254 eV

black line

Input Degeneracy Factor

n-type

$$N_{\rm D}^{+} = N_{\rm D}\left[1-\frac{1}{1+\frac{1}{g}\exp\left(\frac{E_{\rm D}-E_{\rm F}}{kT}\right)}\right]$$

g = 2

Detemine Density and Energy Level

Peak Temperature =137.3 K

Peak Value =2.29E+38 $\mathrm{cm^{-6}\,eV^{-2.5}}$

red line

Density: $N_{\rm D1}$ =7.10E+16 $\mathrm{cm^{-3}}$

Energy Level: $\Delta E_{\rm D1}$=0.051 eV

Compensating Density: $N_{\rm com}$ =-3.48E+16 $\mathrm{cm^{-3}}$

F:\FCCS1_0\Example\3C-SiC\n3CSiC1.H1

Donor1

Peak2

Donor2
51 meV
$7.1\mathrm{x}10^{16}$ $\mathrm{cm^{-3}}$

Donor3

Free Windows Application software:

See at Web site http://www.osakac.ac.jp/labs/matsuura/

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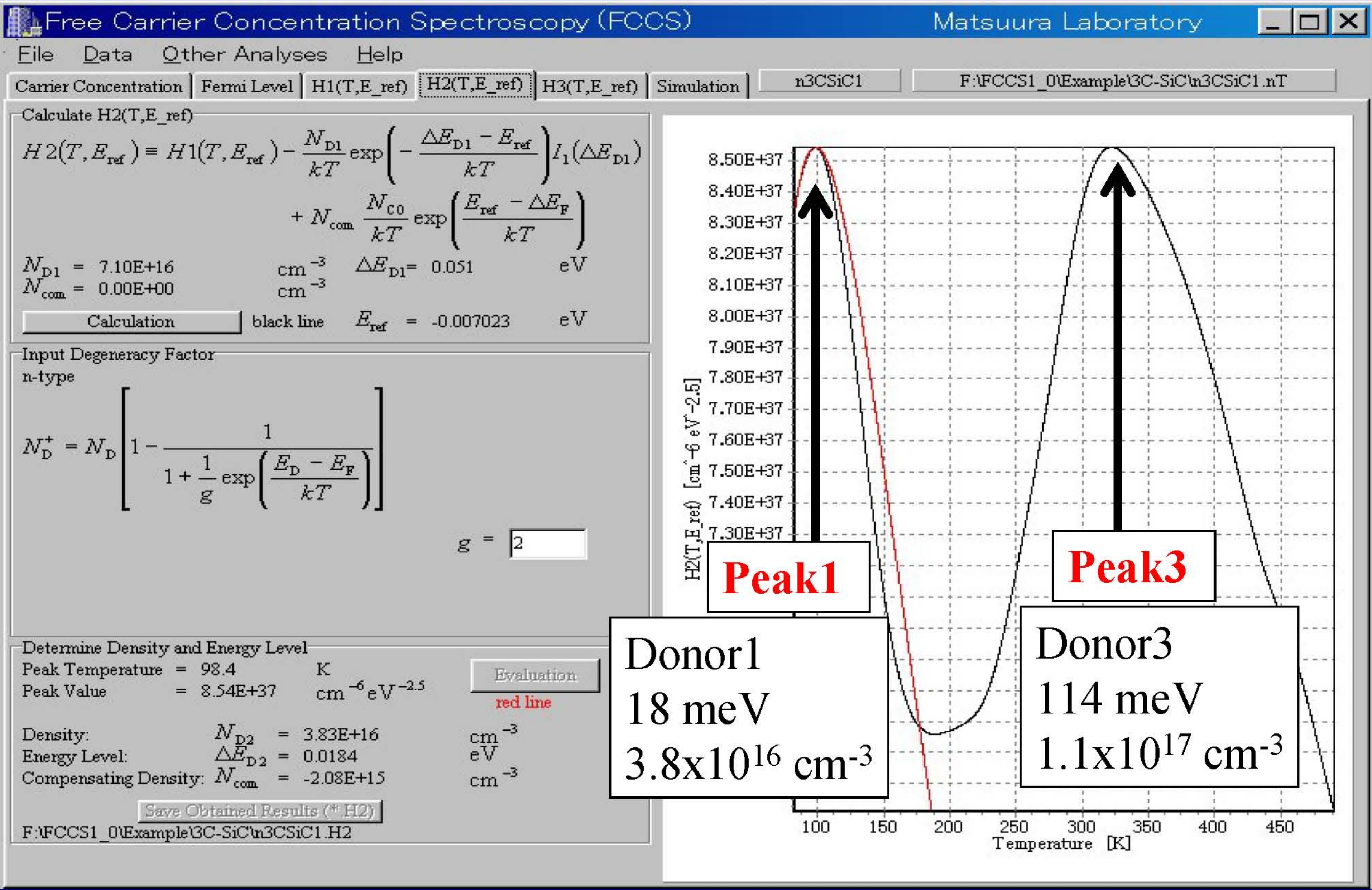

Calculate H2(T,E_ref)

$$H2(T,E_{\mathrm{ref}}) \equiv H1(T,E_{\mathrm{ref}}) - \frac{N_{\mathrm{D1}}}{kT}\exp\left(-\frac{\Delta E_{\mathrm{D1}} - E_{\mathrm{ref}}}{kT}\right) I_1(\Delta E_{\mathrm{D1}}) + N_{\mathrm{com}}\frac{N_{\mathrm{C0}}}{kT}\exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right)$$

N_{D1} = 7.10E+16 cm^{-3} ΔE_{D1} = 0.051 eV

N_{com} = 0.00E+00 cm^{-3}

black line E_{ref} = -0.007023 eV

Input Degeneracy Factor

n-type

$$N_{\mathrm{D}}^{+} = N_{\mathrm{D}}\left[1 - \frac{1}{1 + \frac{1}{g}\exp\left(\frac{E_{\mathrm{D}} - E_{\mathrm{F}}}{kT}\right)}\right]$$

g = 2

Determine Density and Energy Level

Peak Temperature = 98.4 K

Peak Value = 8.54E+37 $\mathrm{cm}^{-6}\mathrm{eV}^{-2.5}$

red line

Density: N_{D2} = 3.83E+16 cm^{-3}

Energy Level: ΔE_{D2} = 0.0184 eV

Compensating Density: N_{com} = -2.08E+15 cm^{-3}

F:\FCCS1_0\Example\3C-SiC\n3CSiC1.H2

Peak1

Donor1
18 meV
3.8×10^{16} cm^{-3}

Peak3

Donor3
114 meV
1.1×10^{17} cm^{-3}

The FCCS signal theoretically-derived

$$H(T,E_{\mathrm{ref}}) = \sum_i \frac{N_i}{kT}\exp\left(-\frac{\Delta E_i - E_{\mathrm{ref}}}{kT}\right) I(\Delta E_i)$$

$$-\frac{N_{\mathrm{V0}} N_{\mathrm{comp}}}{kT}\exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right)$$

The function

$$\frac{N_i}{kT}\exp\left(-\frac{\Delta E_i - E_{\mathrm{ref}}}{kT}\right)$$

has a peak value of $$\frac{N_i}{kT_{\mathrm{peak}i}}\exp(-1)$$

at $$\frac{\Delta E_i - E_{\mathrm{ref}}}{k}$$

Results from p(T) by FCCS

	Before irradiation	0.2 MeV	4.6 MeV
ΔE_{Al} [meV]	203 (203)	217	206
N_{Al} [x10^{15} cm^{-3}]	5.2 (6.2)	4.3	0.82
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$\mathrm{N}_{\mathrm{comp}}$ represents the density of hole traps deeper than 360 meV and donor-like defect.