Mechanisms of changes of hole concentration in Al-doped 6H-SiC by electron irradiation and annealing

Hideharu Matsuura, Hideki Yanagisawa, Kozo Nishino,
Yoshiko Myojin, Takunori Nojiri, Yukei Matsuyama
Osaka Electro-Communication University

Takeshi Ohshima
Japan Atomic Energy Agency

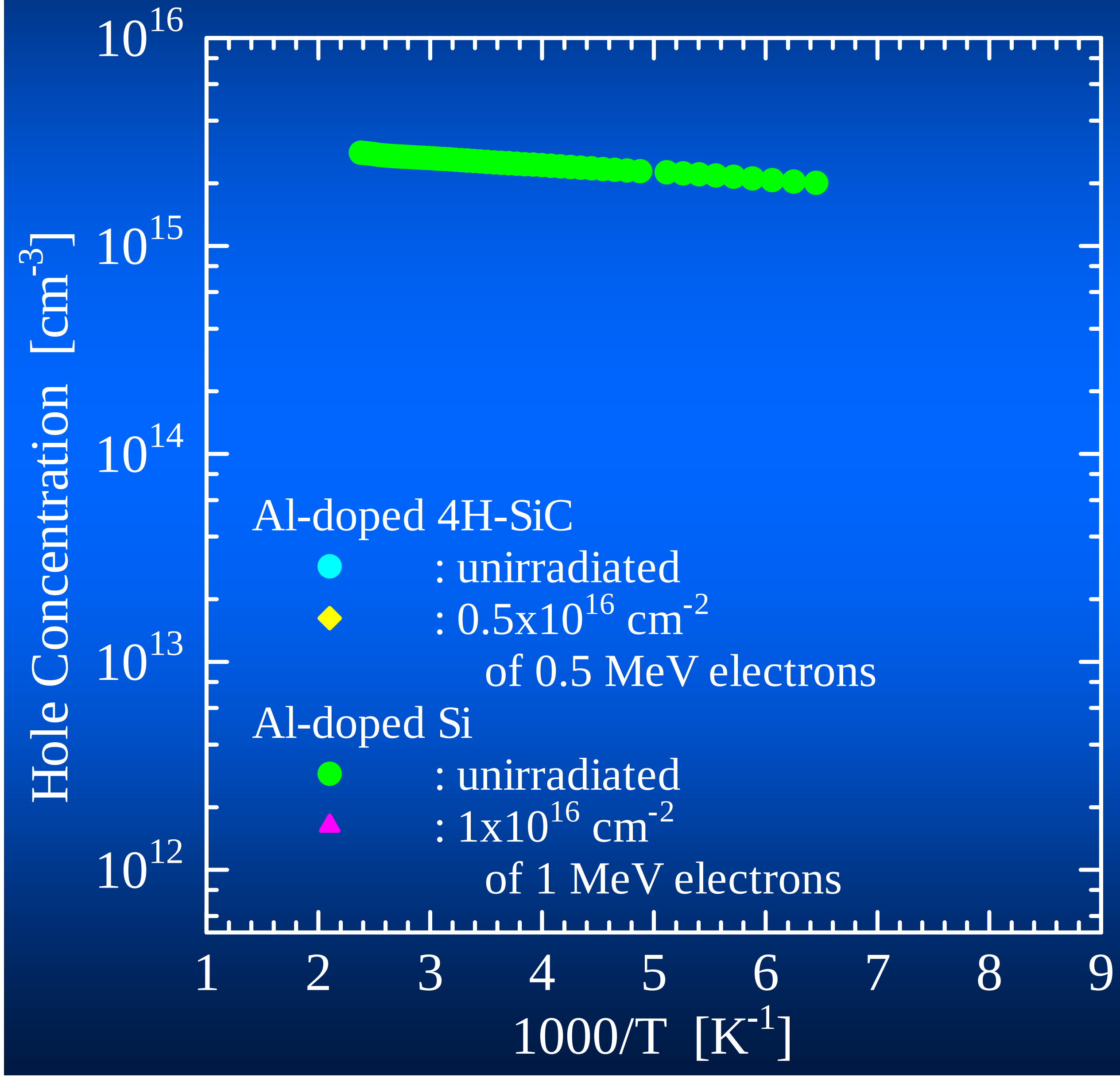
International Conference on Defects in Semiconductors(ICDS-25)
20 July, 2009, St. Petersburg, Russia

Background of our study

Silicon carbide (SiC) is a promising wide bandgap semiconductor for fabricating high-power and high-frequency electronic devices capable of operating at elevated temperature under radiation environment.

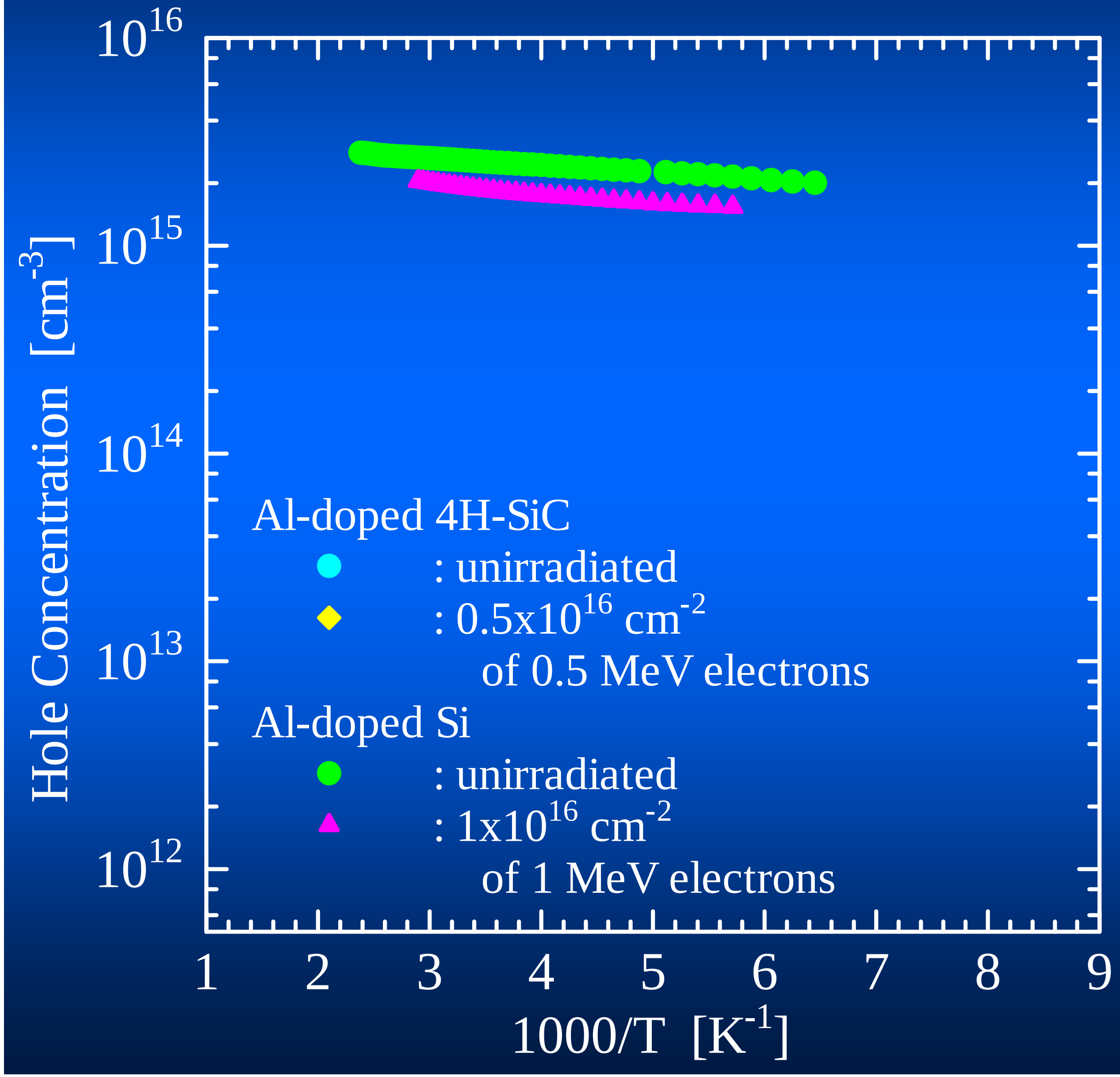
In order to understand the radiation-degradation of SiC electronic devices, changes of properties in SiC by radiation should be investigated.

Comparison of radiation resistance of Si and SiC



Al-doped Si

Comparison of radiation resistance of Si and SiC



Al-doped Si

Irradiation conditions

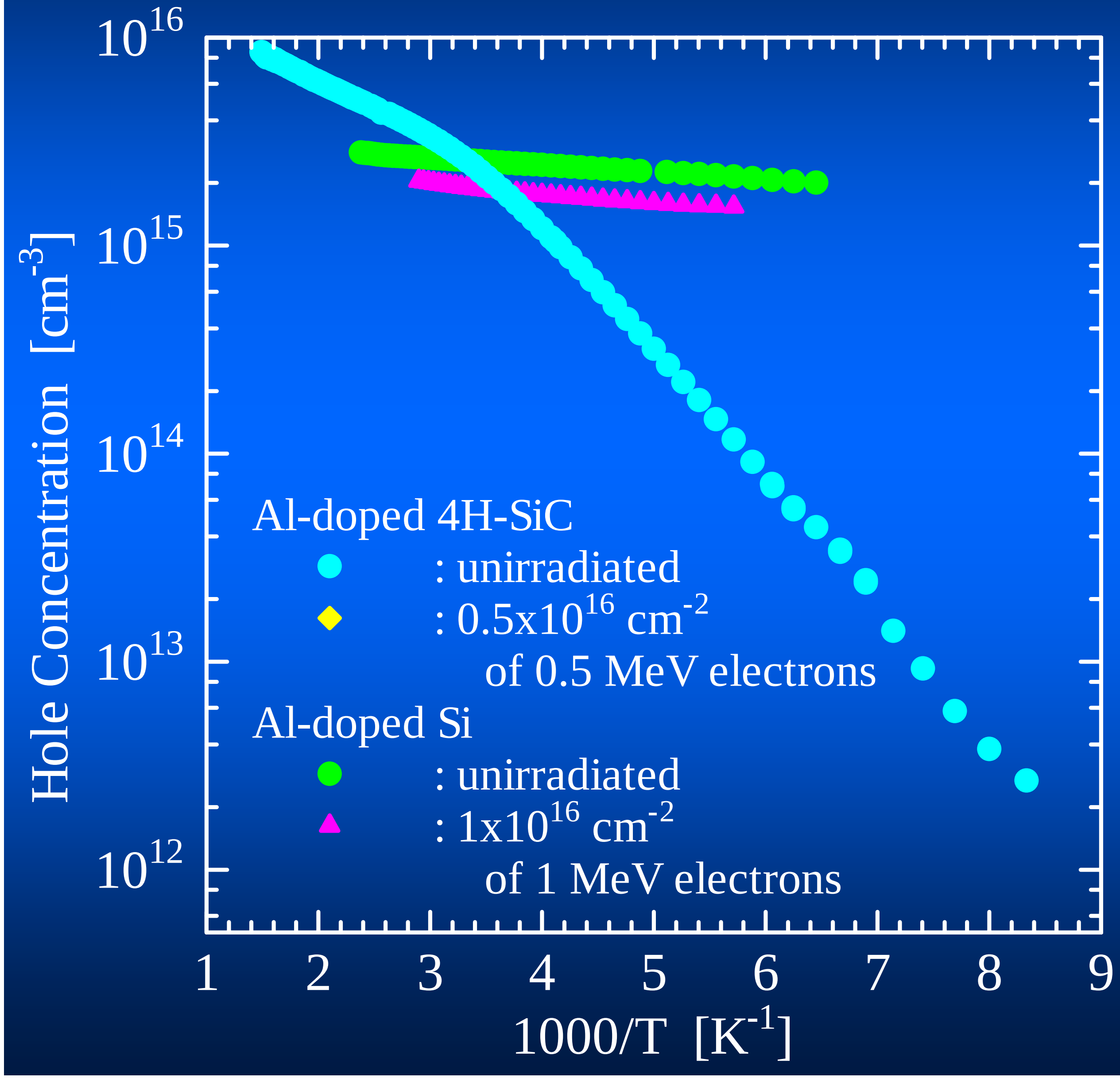
1 MeV electrons

1×10^{16} cm^{-2} fluence

⇩

p(T) decreased slightly.

Comparison of radiation resistance of Si and SiC



Al-doped Si

Irradiation conditions

1 MeV electrons

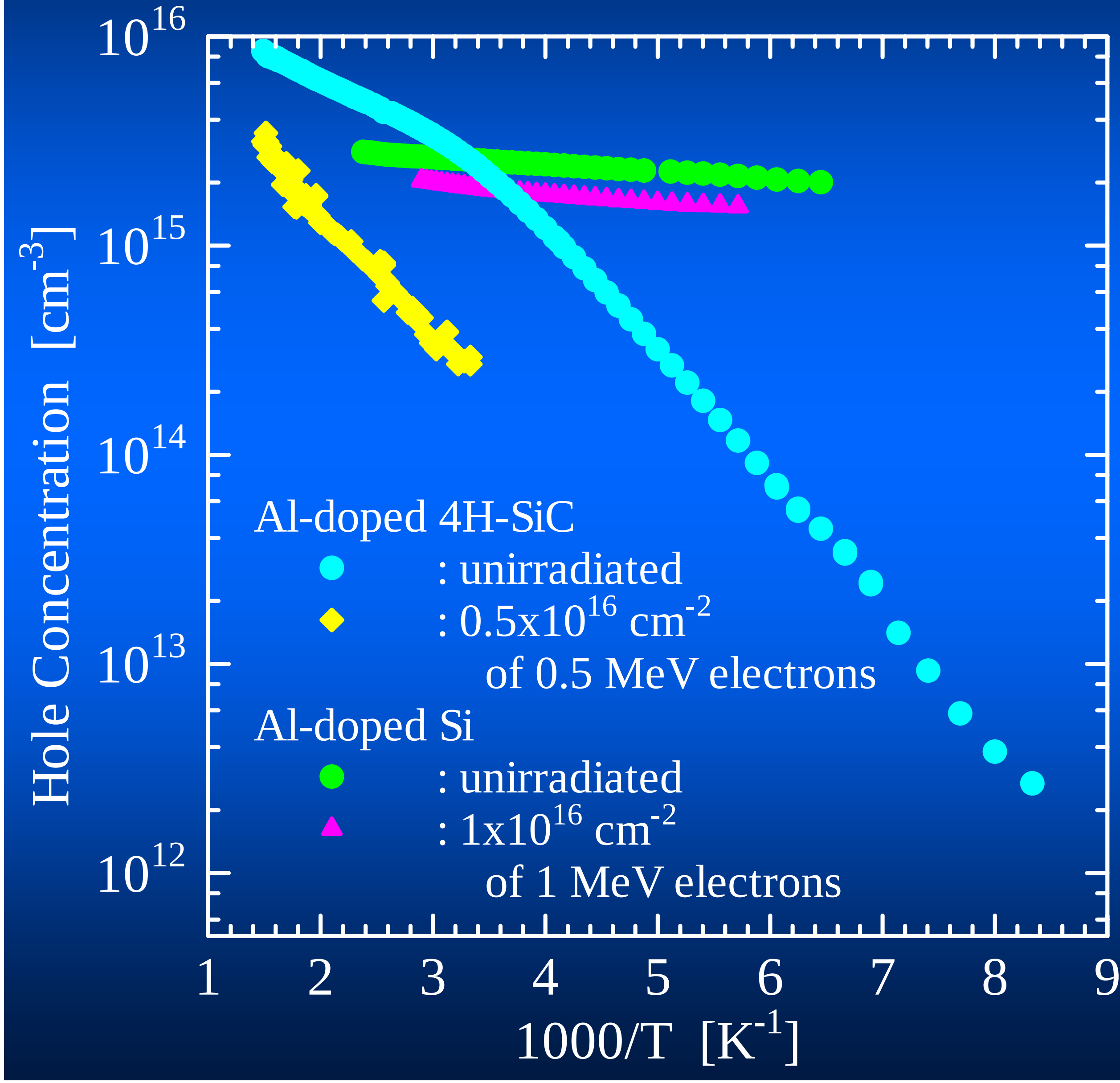
1x10^{16} cm^{-2} fluence

⇩

p(T) decreased slightly.

Al-doped 4H-SiC

Comparison of radiation resistance of Si and SiC



Al-doped Si

Irradiation conditions

1 MeV electrons

1×10^{16} cm^{-2}

⇩

p(T) decreased slightly.

Al-doped 4H-SiC

Irradiation conditions

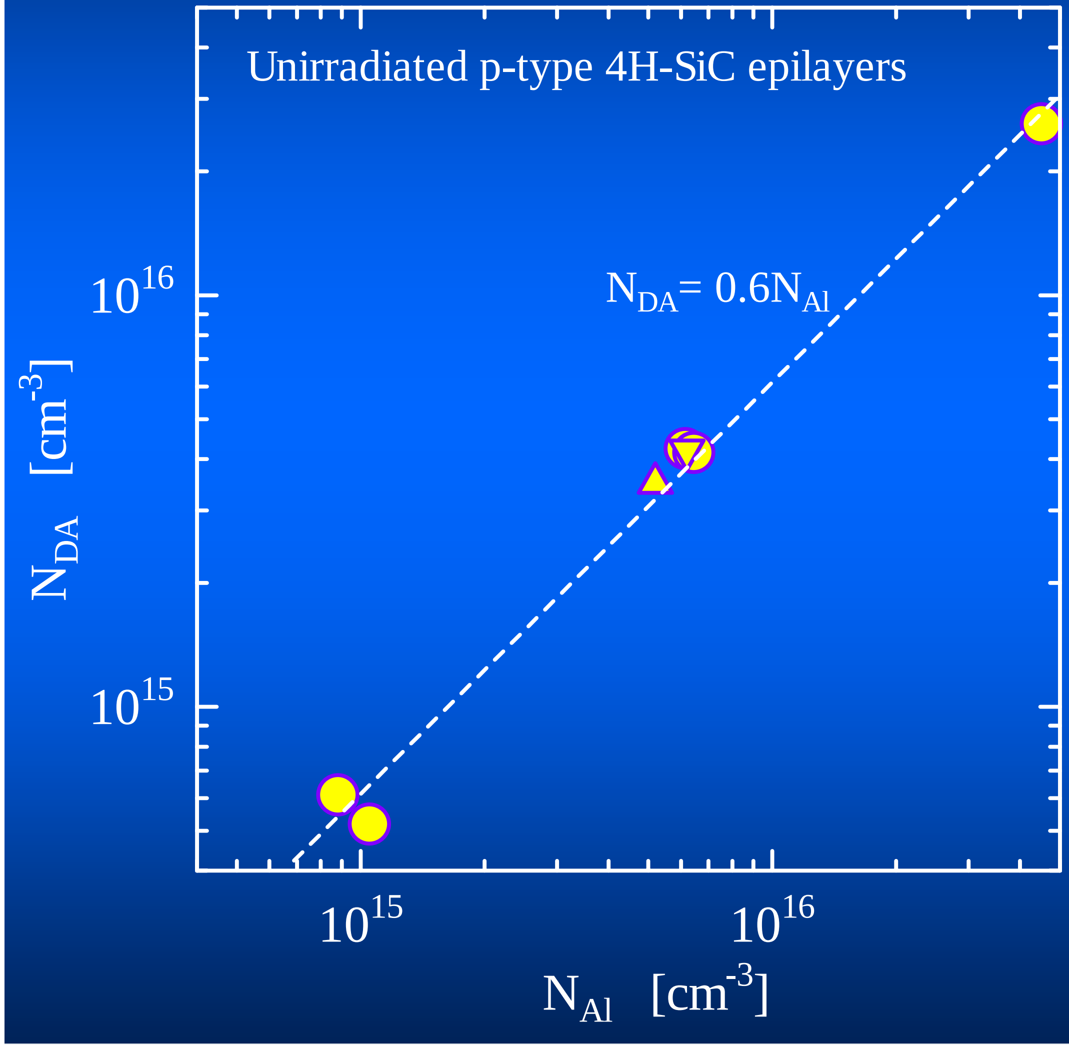
0.5 MeV electrons

0.5×10^{16} cm^{-2} fluence

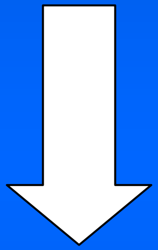
⇩

p(T) decreased significantly.

Relationship between N_{Al} and N_{DA} in unirradiated Al-doped 4H-SiC epilayer

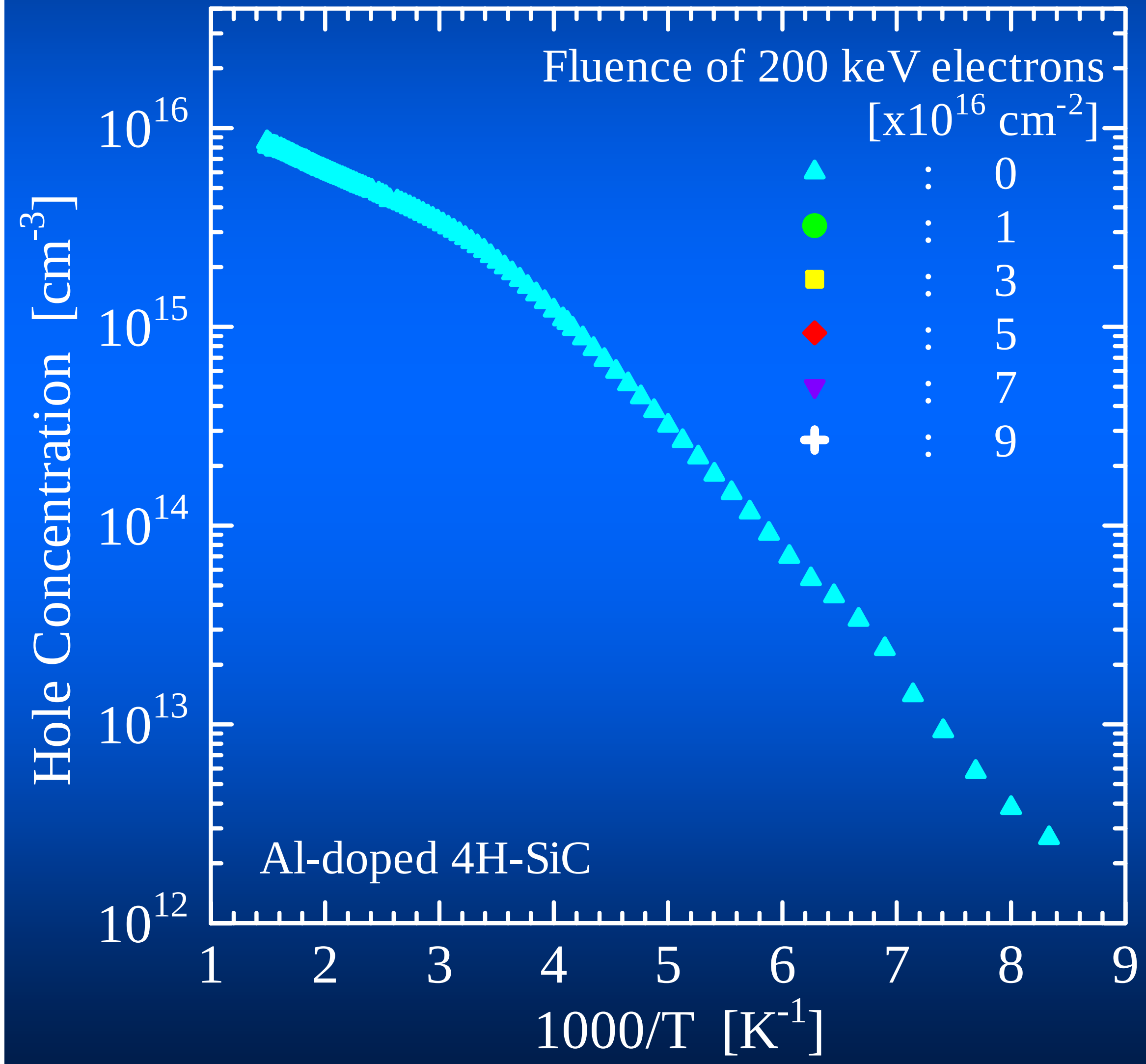


$$N_{DA} = 0.6 \times N_{Al}$$



The unknown deep acceptor is most likely related to Al

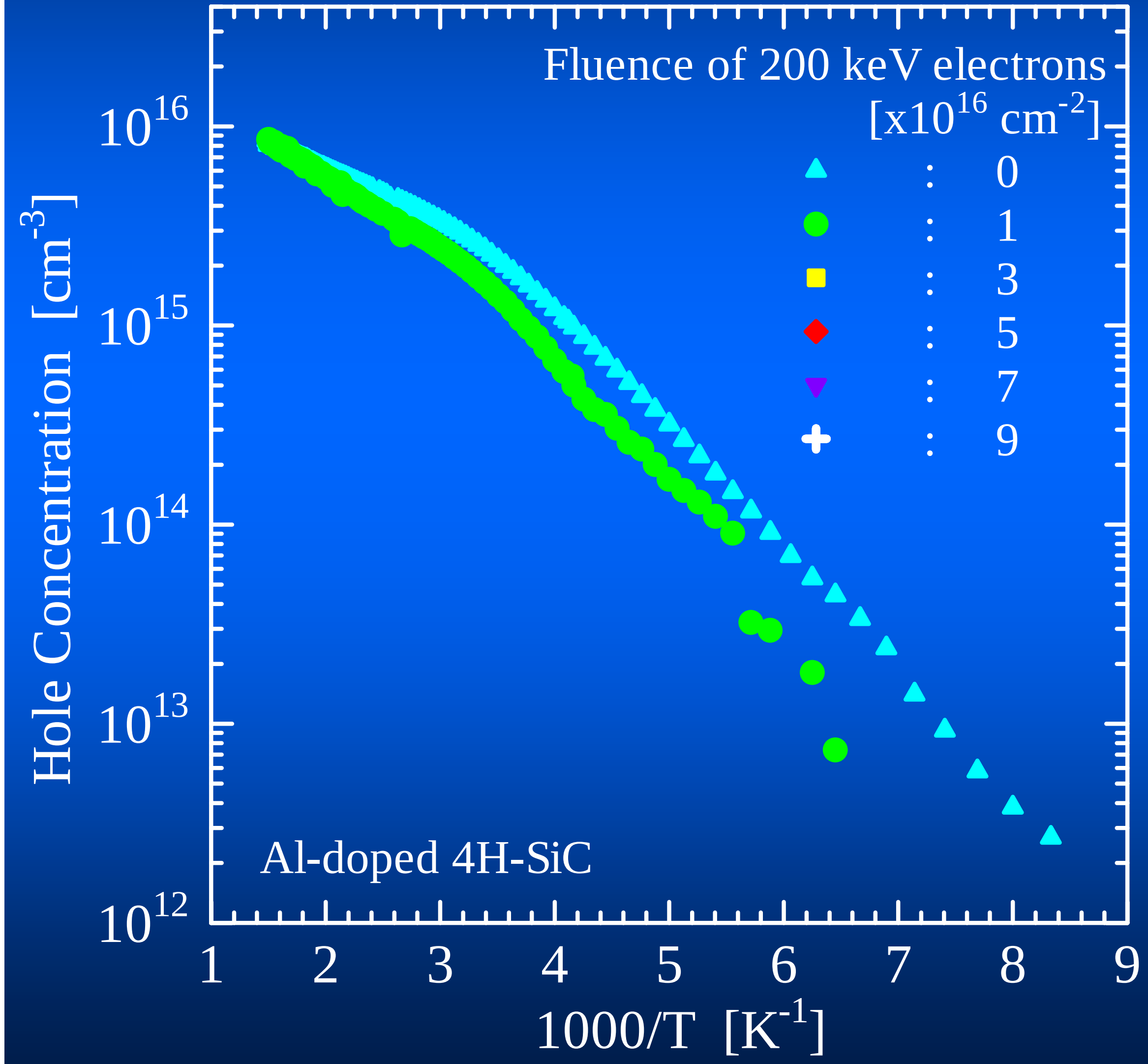
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

0

Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation

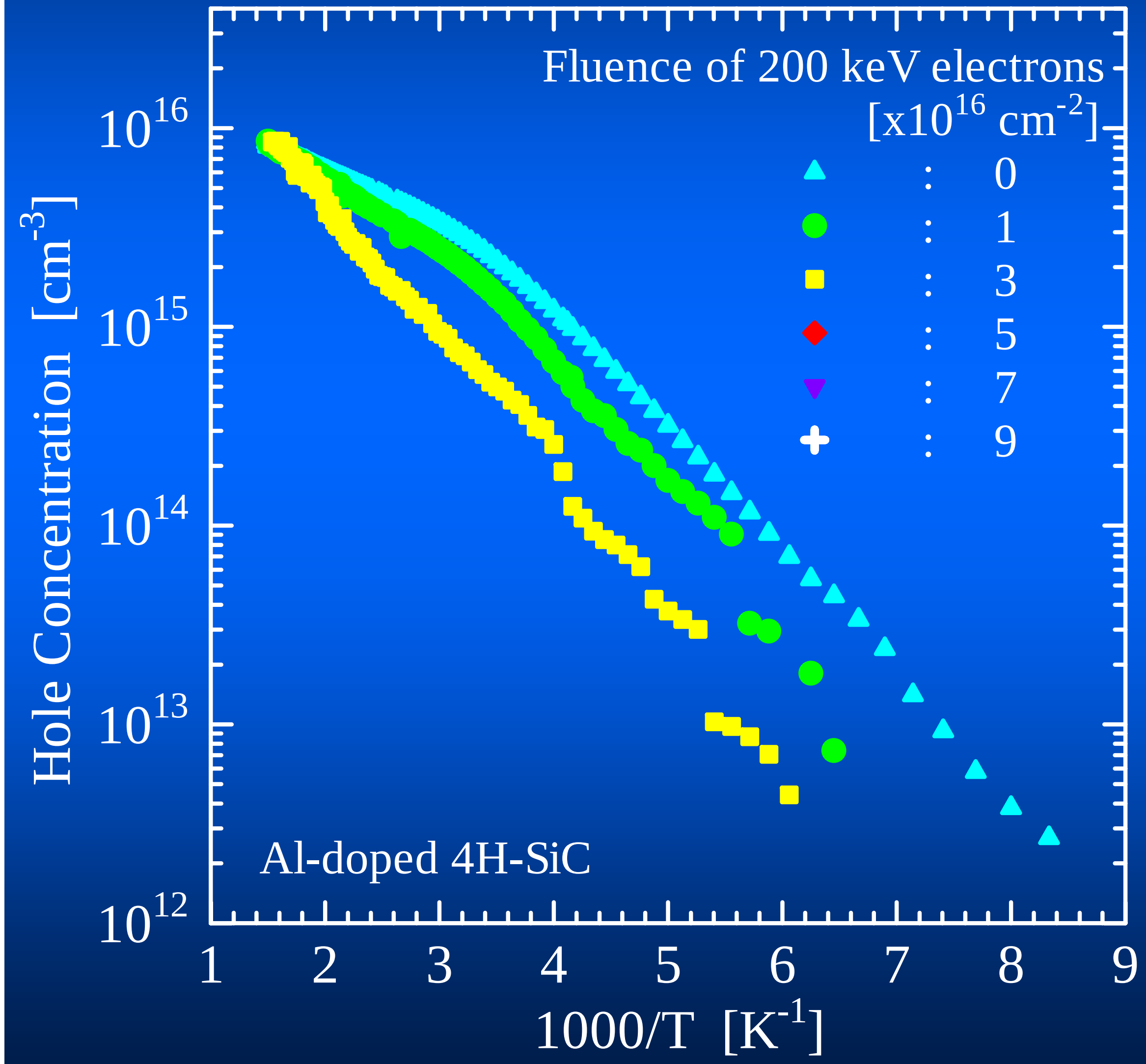


Fluence [cm^{-2}]

1×10^{16}

Osaka Electro-Communication University

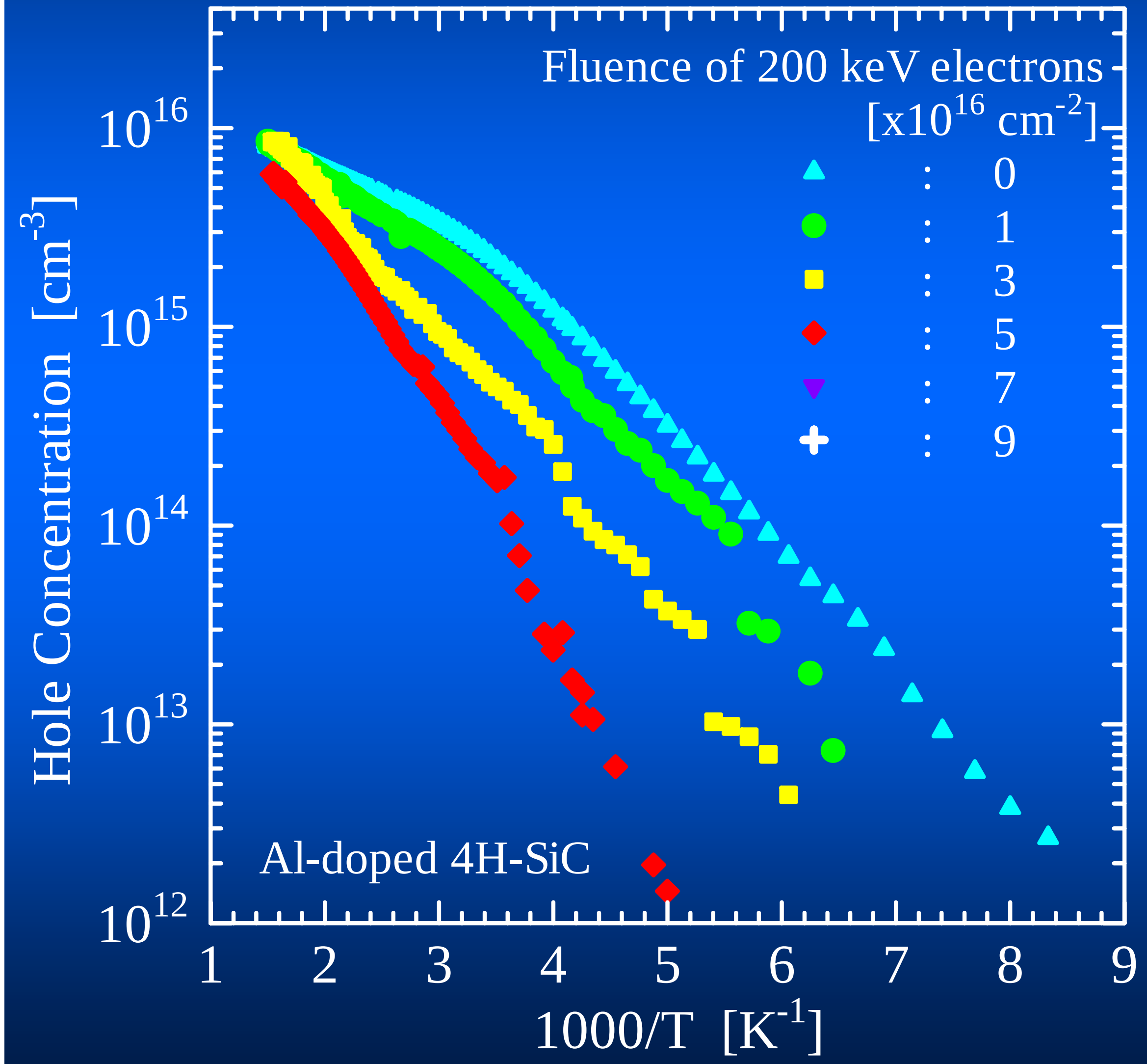
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

3×10^{16}

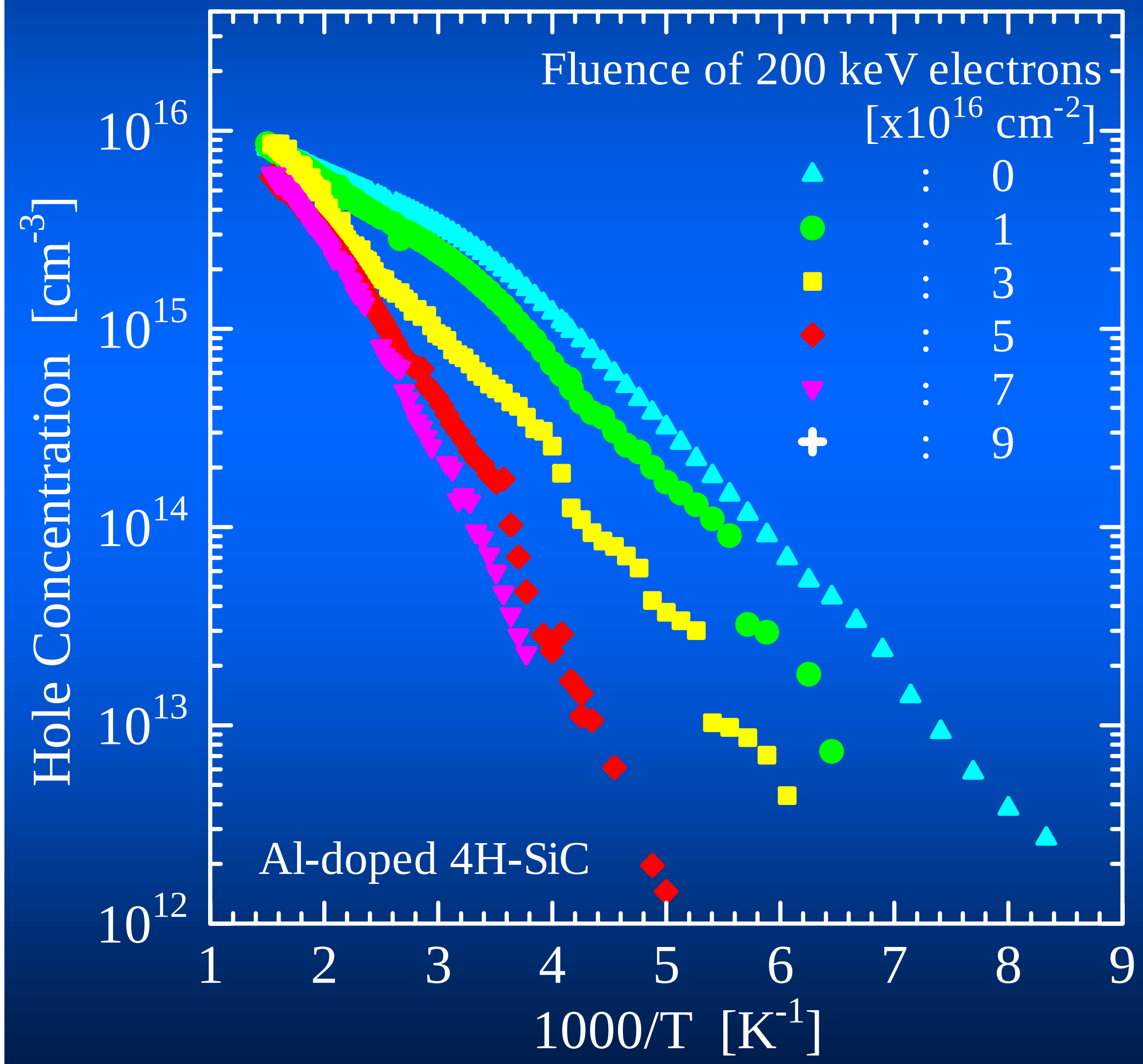
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

5×10^{16}

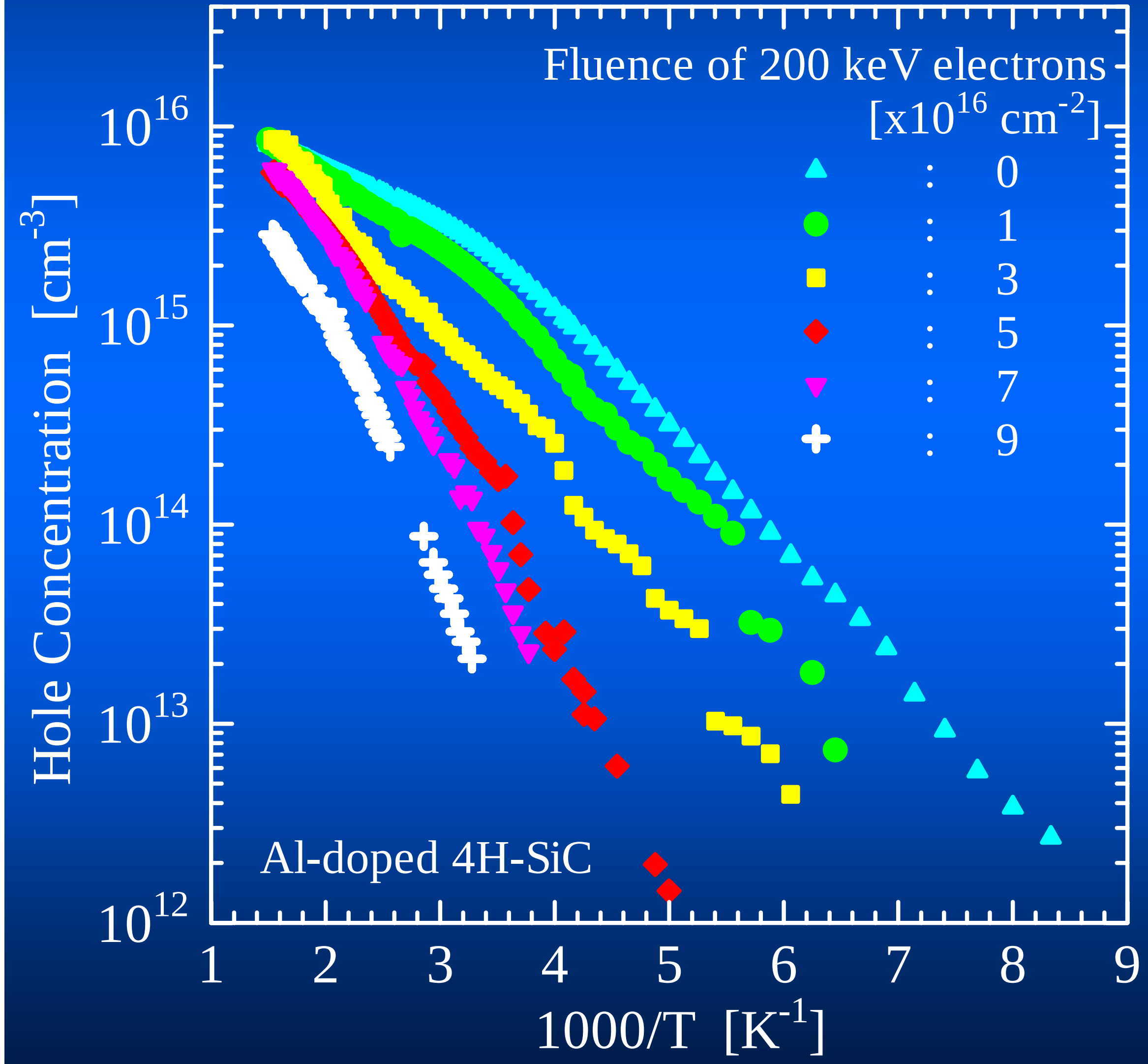
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

7×10^{16}

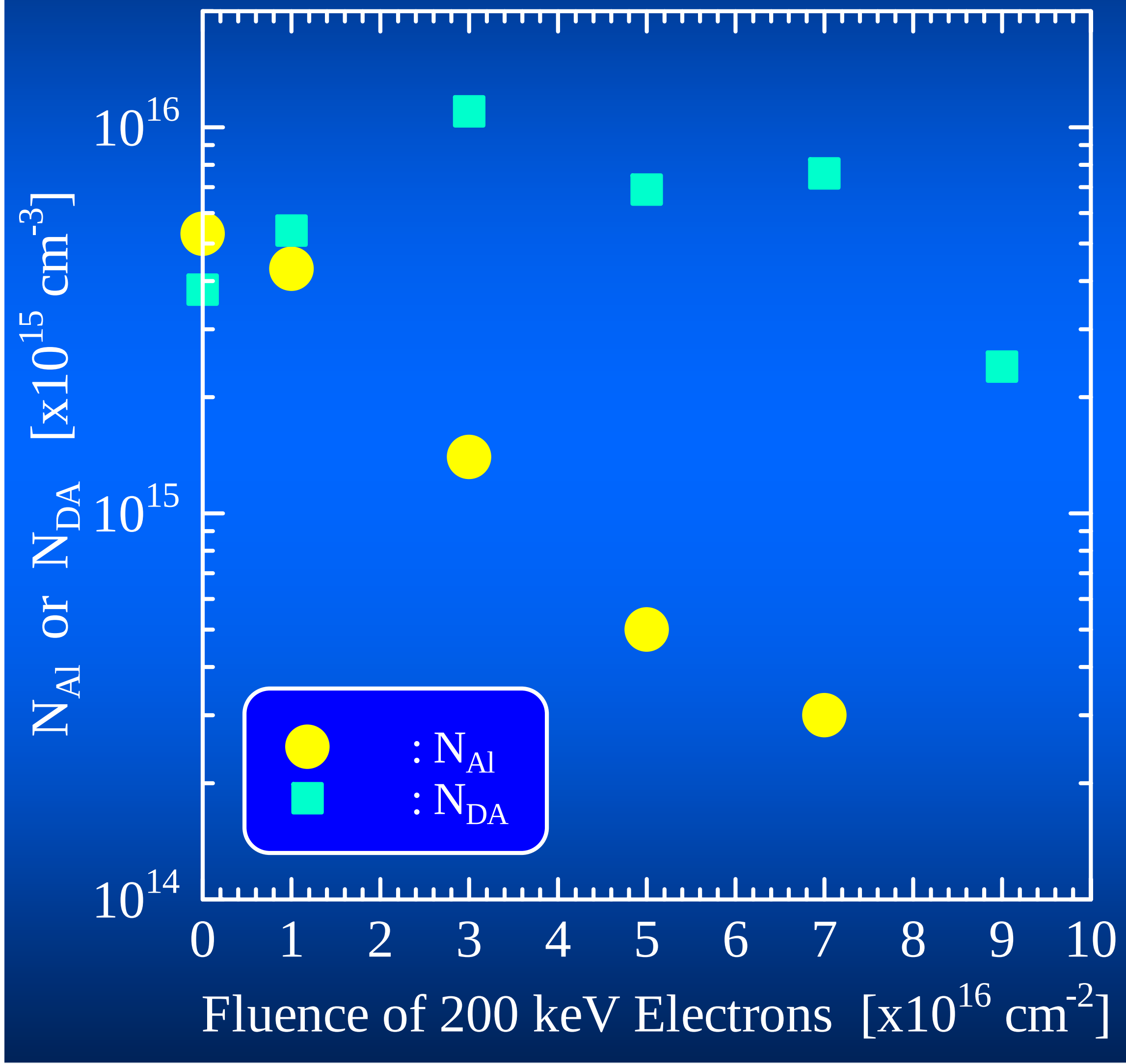
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



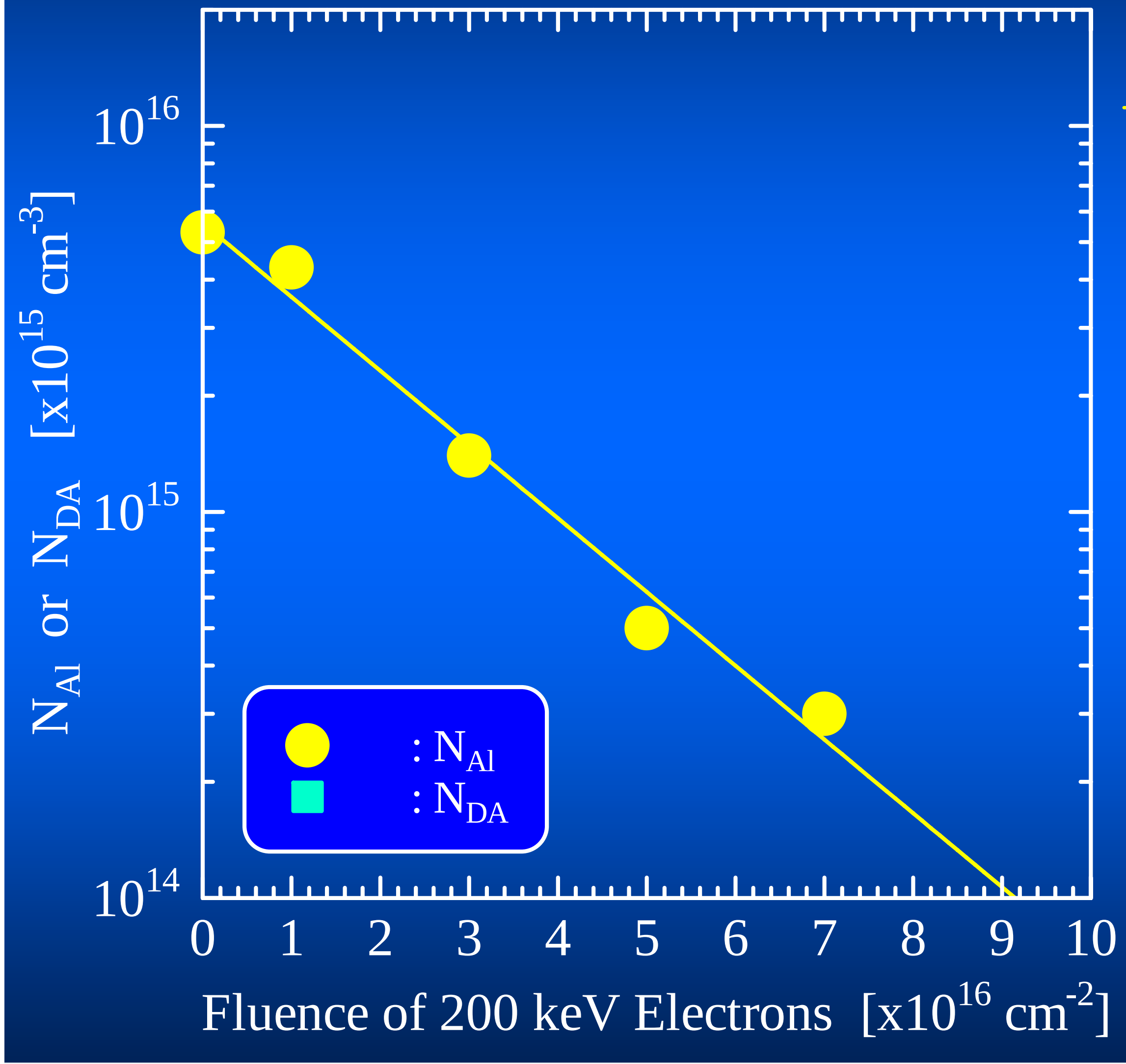
Fluence [cm^{-2}]

9×10^{16}

Fluence Dependence of N_{Al} and N_{DA} in 4H-SiC



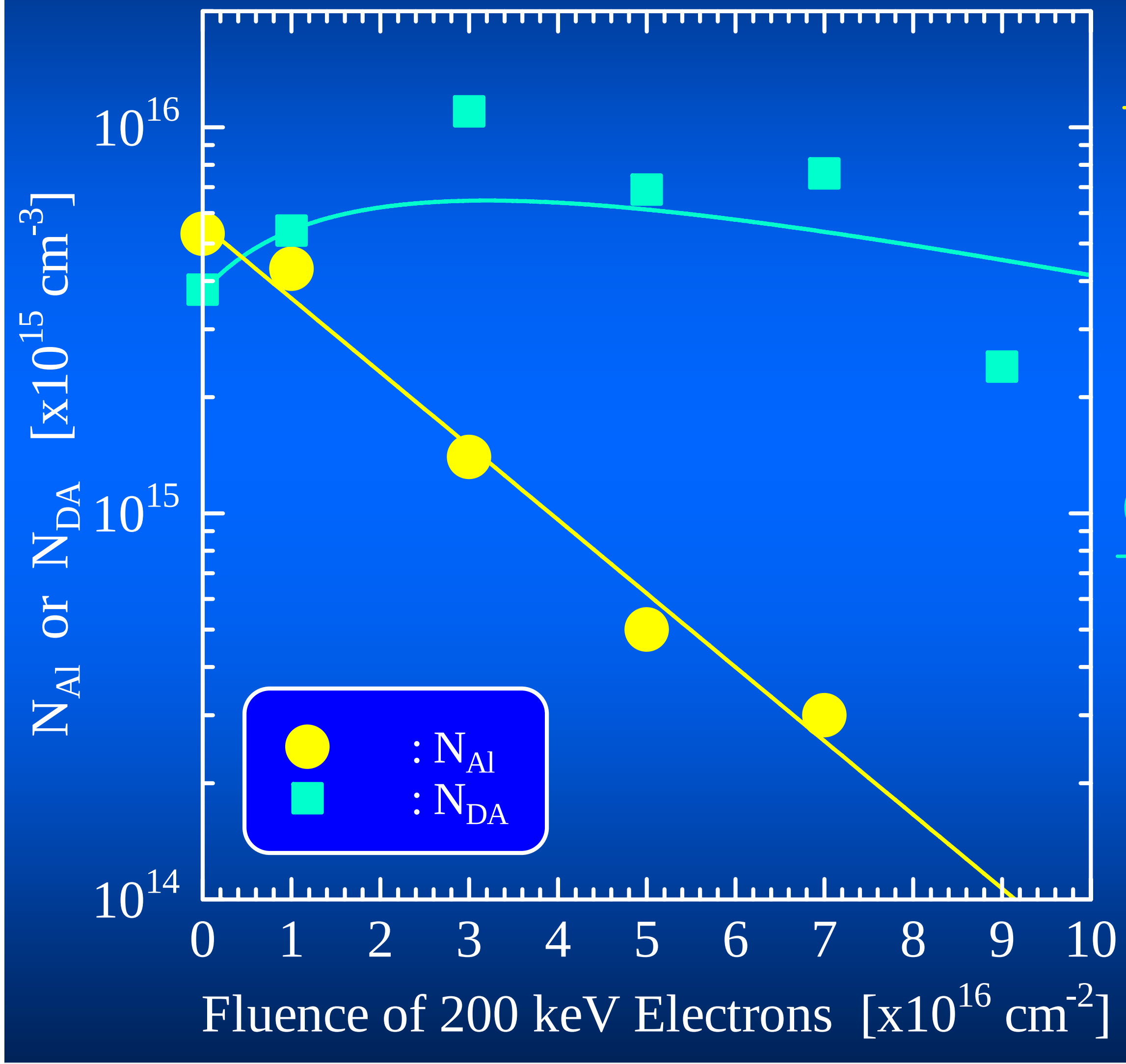
Fluence Dependence of N_{Al} and N_{DA} in 4H-SiC



$$\frac{dN_{Al}(\Phi)}{d\Phi} = -\kappa_{Al} N_{Al}(\Phi)$$

$$\kappa_{Al} = 4.4 \times 10^{-17} \ \ \mathrm{cm}^2$$

Fluence Dependence of N_{Al} and N_{DA} in 4H-SiC



$$\frac{dN_{Al}(\Phi)}{d\Phi} = -\kappa_{Al} N_{Al}(\Phi)$$

$$\kappa_{Al} = 4.4\times10^{-17}\ \mathrm{cm}^2$$

$$\frac{dN_{DA}(\Phi)}{d\Phi} = -\frac{dN_{Al}(\Phi)}{d\Phi} - \kappa_{DA} N_{DA}(\Phi)$$

$$\kappa_{DA} = 1.0\times10^{-17}\ \mathrm{cm}^2$$

Motivation of our study

1. Which polytype of SiC is radiation-resistant?

   How about Al-doped 6H-SiC

2. Why is the p(T) reduced by irradiation?

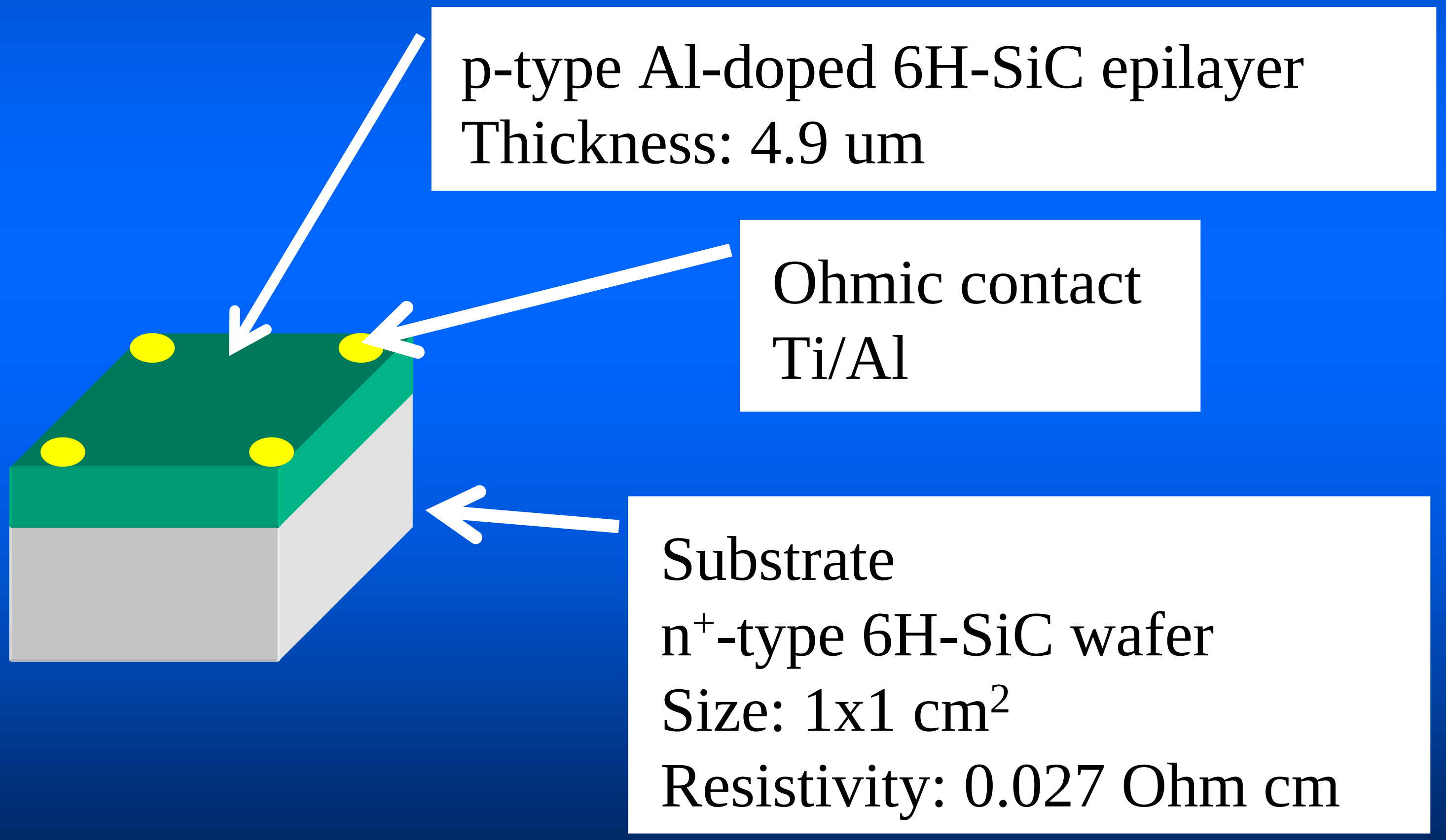
   Increase in compensating density or

   Change of acceptor densities

3. What is the origin of the deep acceptor?

Sample Configuration

Investigation of acceptors and defects in **Al-doped 6H-SiC** from p(T) obtained by Hall-effect measurements

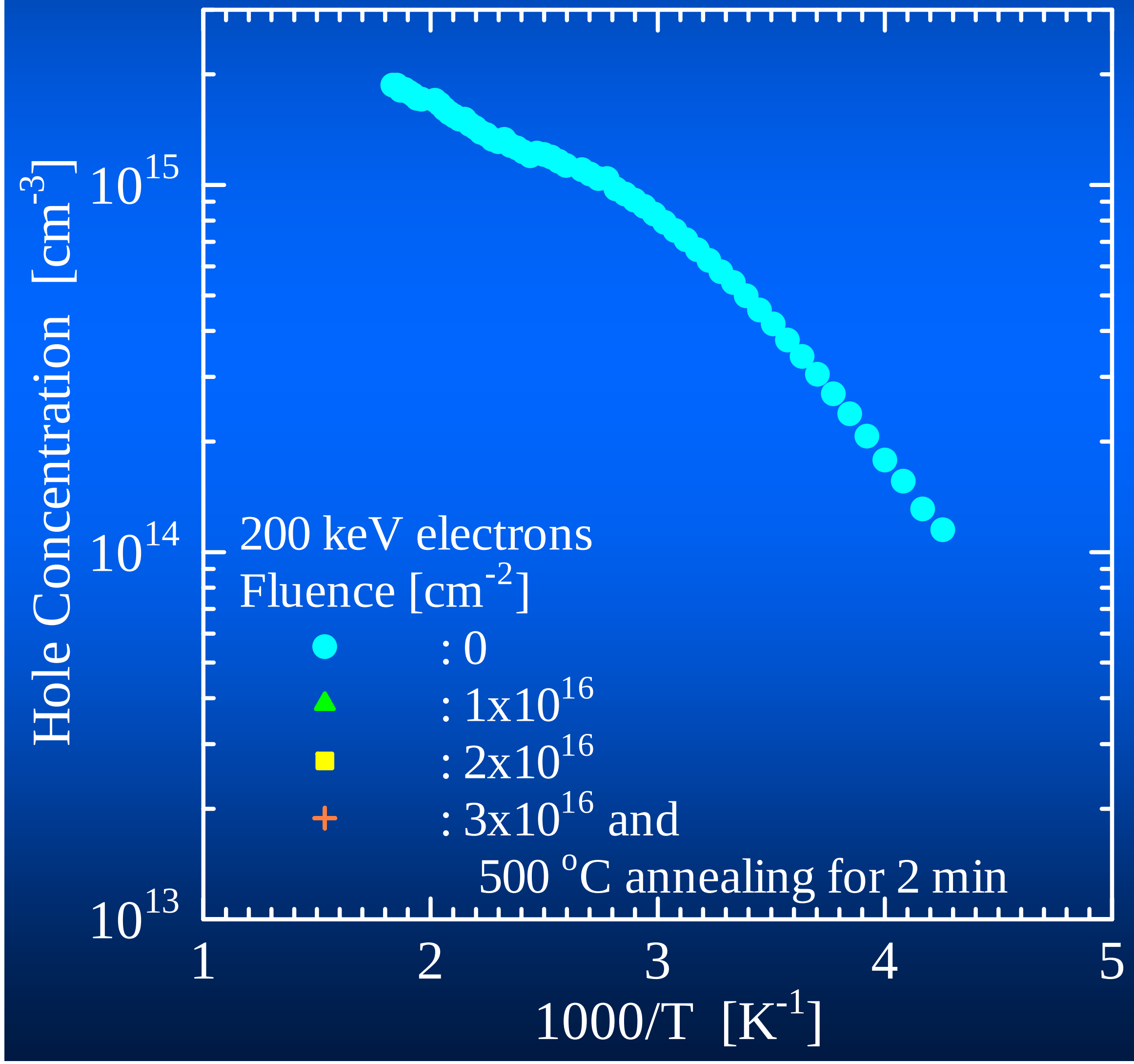


p-type Al-doped 6H-SiC epilayer
Thickness: 4.9 um

Ohmic contact
Ti/Al

Substrate
n^+-type 6H-SiC wafer
Size: 1x1 cm^2
Resistivity: 0.027 Ohm cm

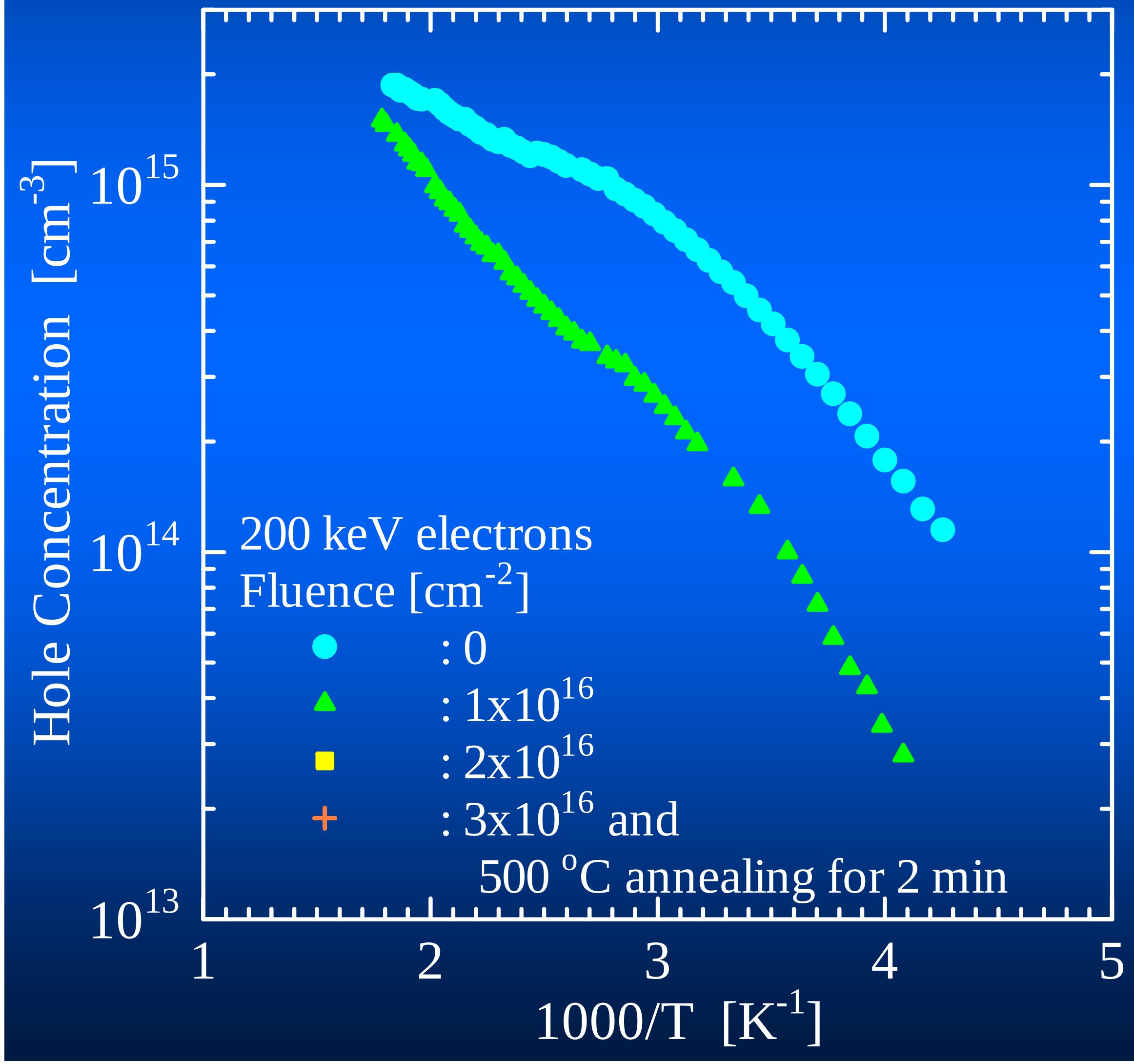
Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

0

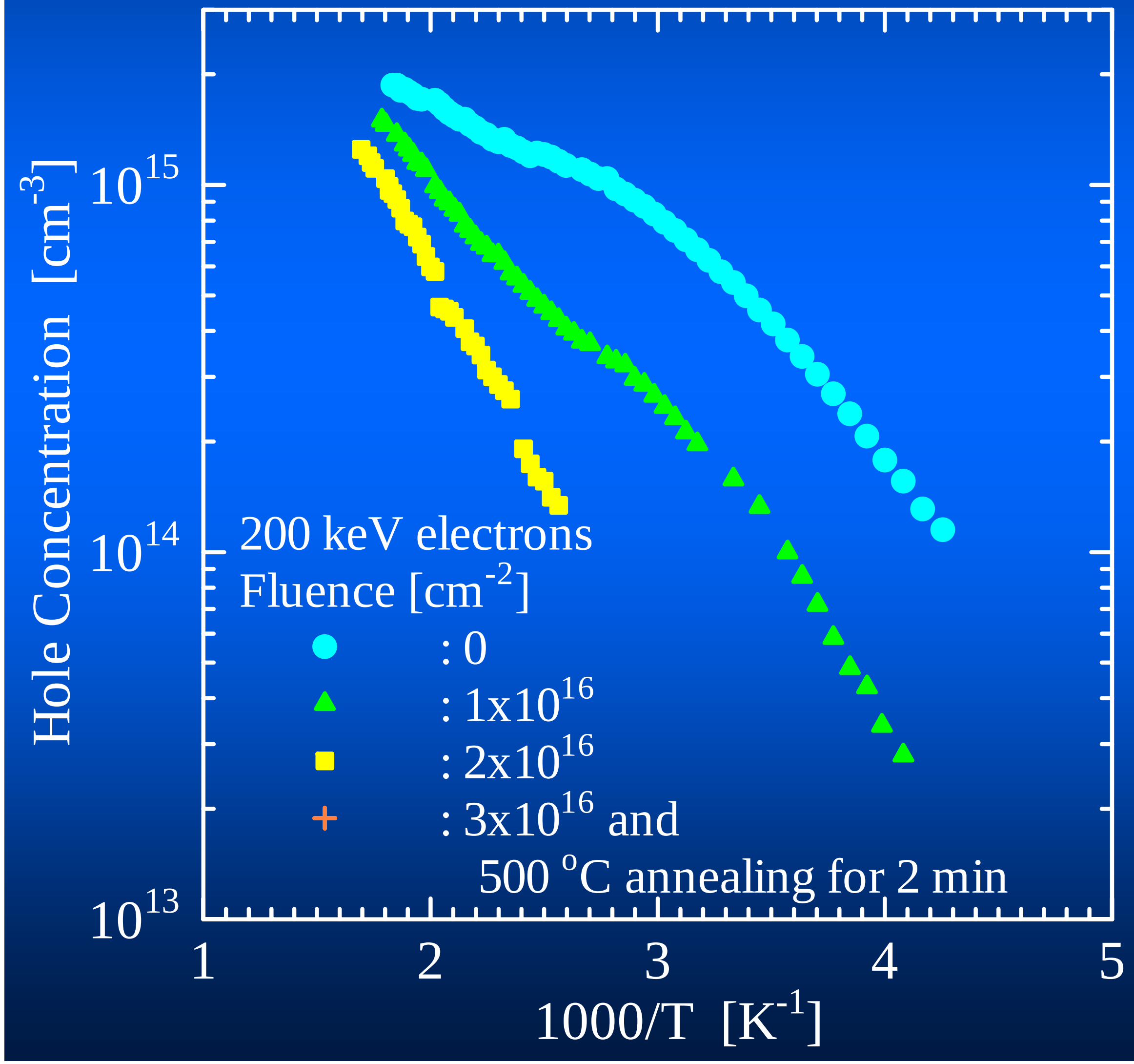
Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

1×10^{16}

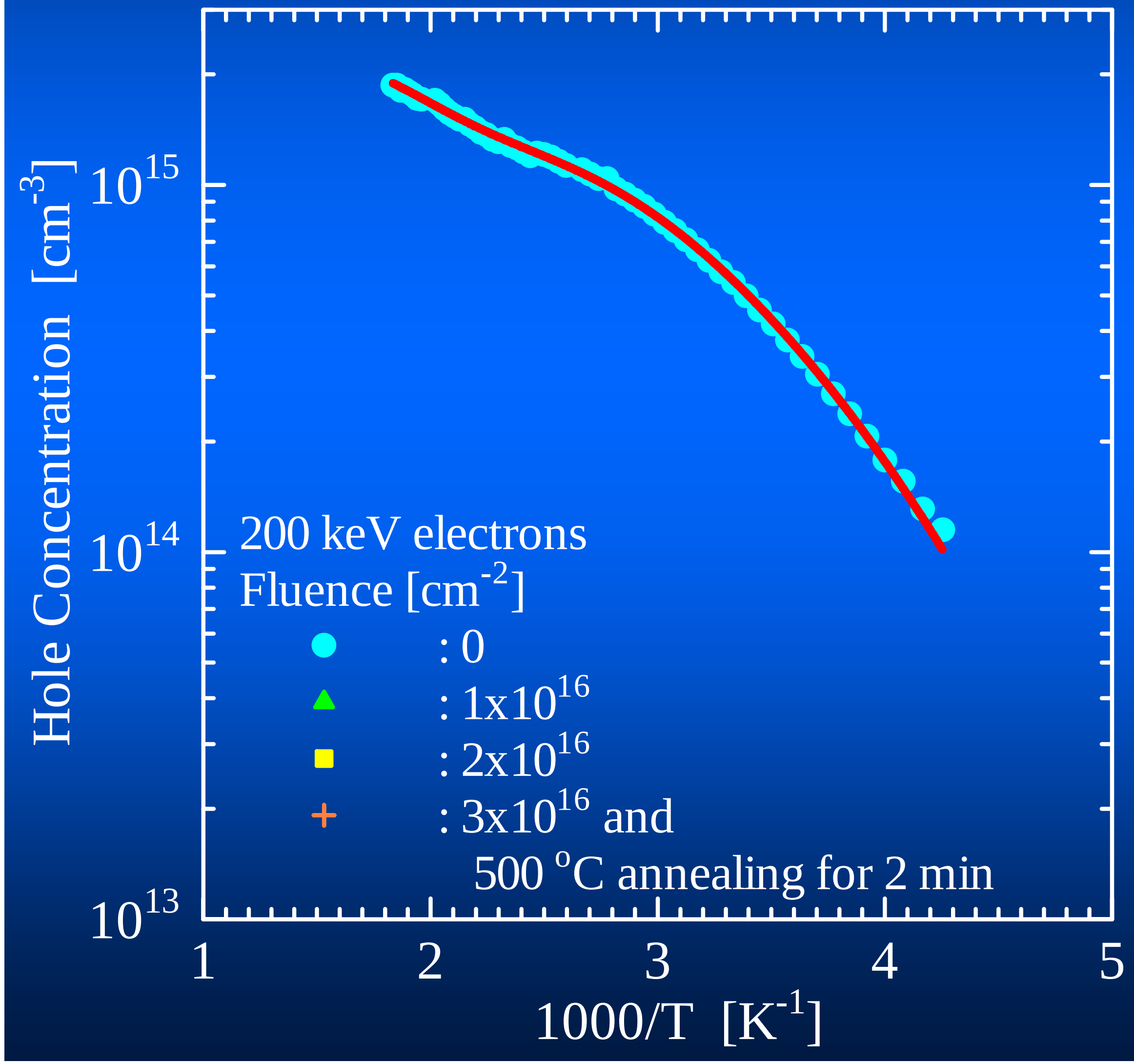
Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

2×10^{16}

Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

0

Simulation Result

$N_{\mathrm{Al}} = 1.6\times10^{15}\,\mathrm{cm}^{-3}$

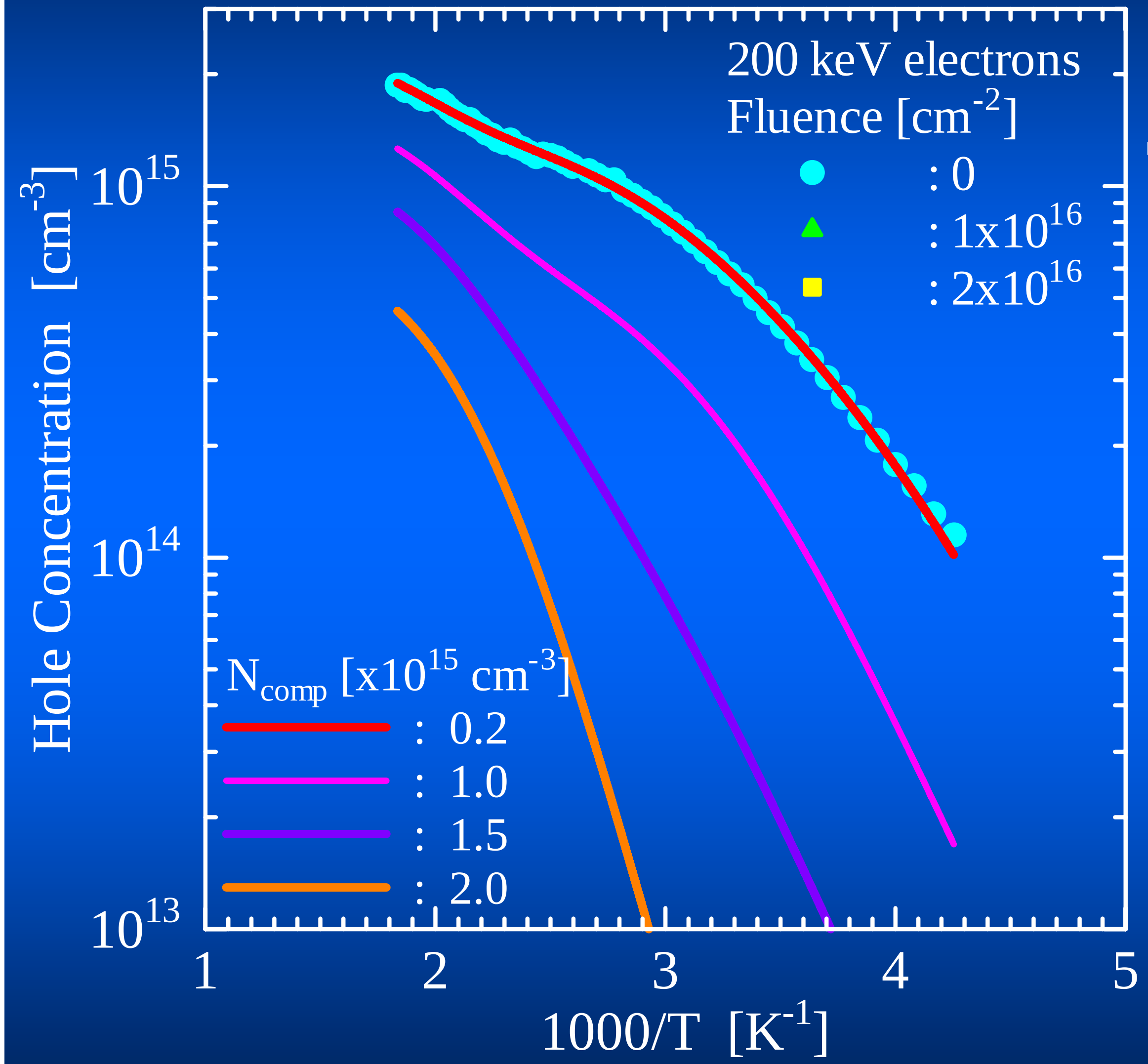
$E_{\mathrm{Al}} = E_{\mathrm{V}} + 0.24\ \mathrm{eV}$

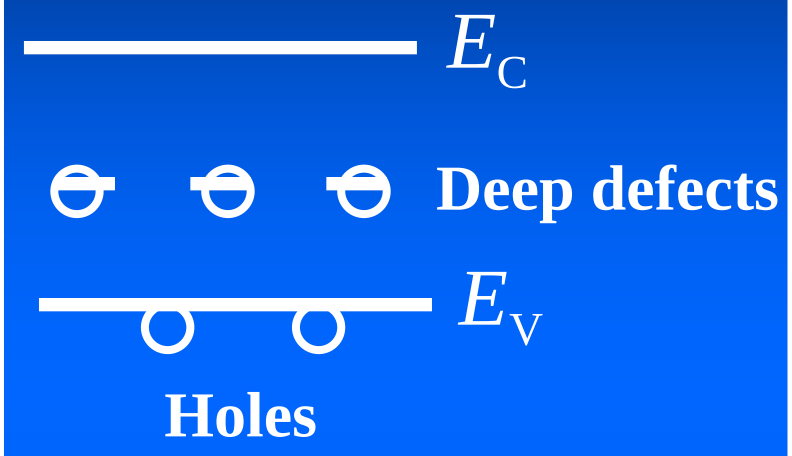
$N_{\mathrm{DA}} = 1.0\times10^{15}\,\mathrm{cm}^{-3}$

$E_{\mathrm{DA}} = E_{\mathrm{V}} + 0.41\ \mathrm{eV}$

$N_{\mathrm{comp}} = 2.6\times10^{14}\,\mathrm{cm}^{-3}$

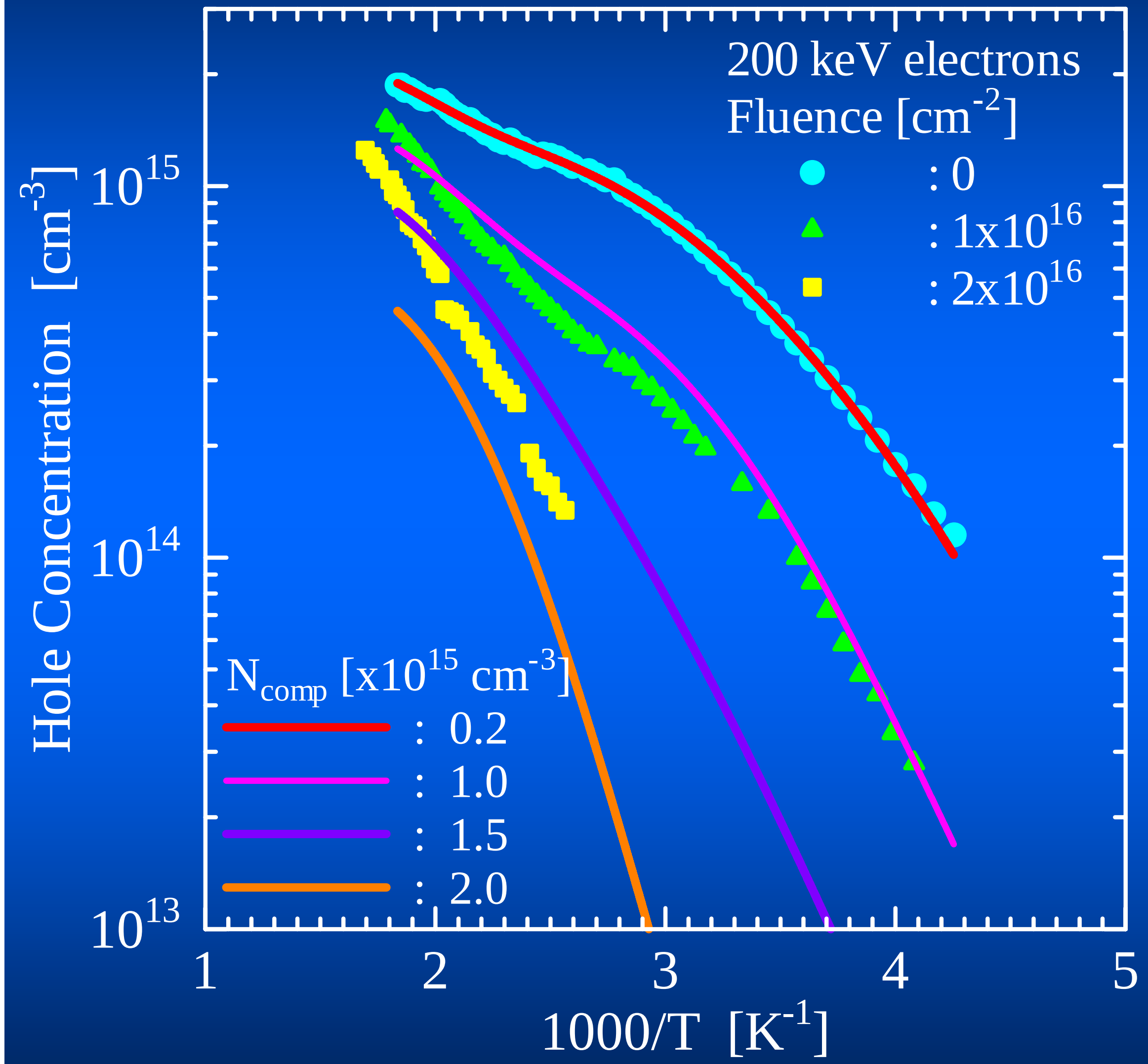
p(T) influenced by compensating density





Using densities and energy levels of two types of acceptors in unirradiated sample, p(T) were simulated with different N$_{comp}$.

p(T) influenced by compensating density

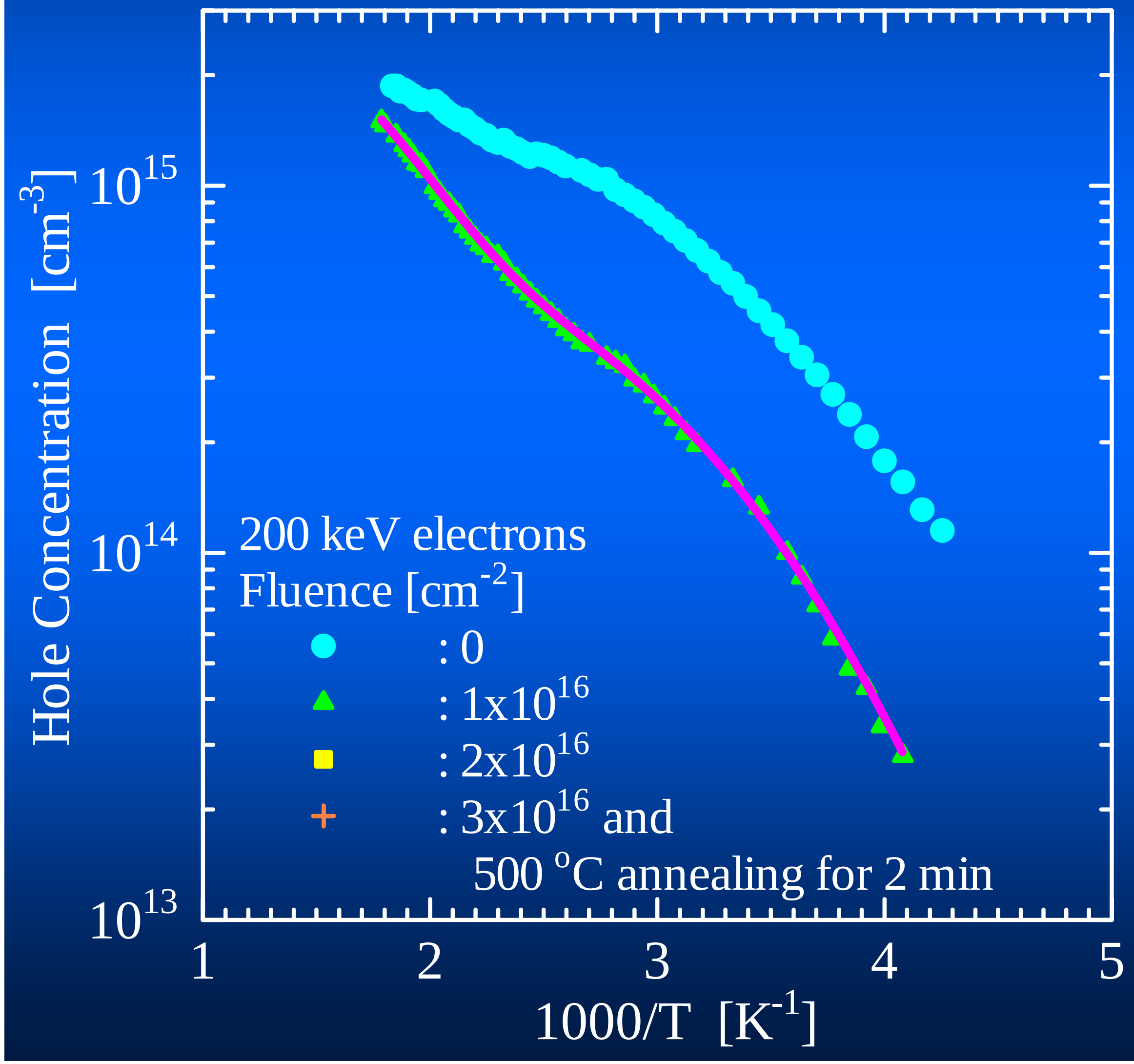


With increasing N$_{comp}$, p(T) values at not only low but also high temperatures were reduced.

Experimental p(T) values at high temperatures were not reduced by irradiation much than simulated.

Acceptor densities should be changed by irradiation.

Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

1×10^{16}

Simulation Result

$N_{Al} = 5.6\times10^{14} cm^{-3}$

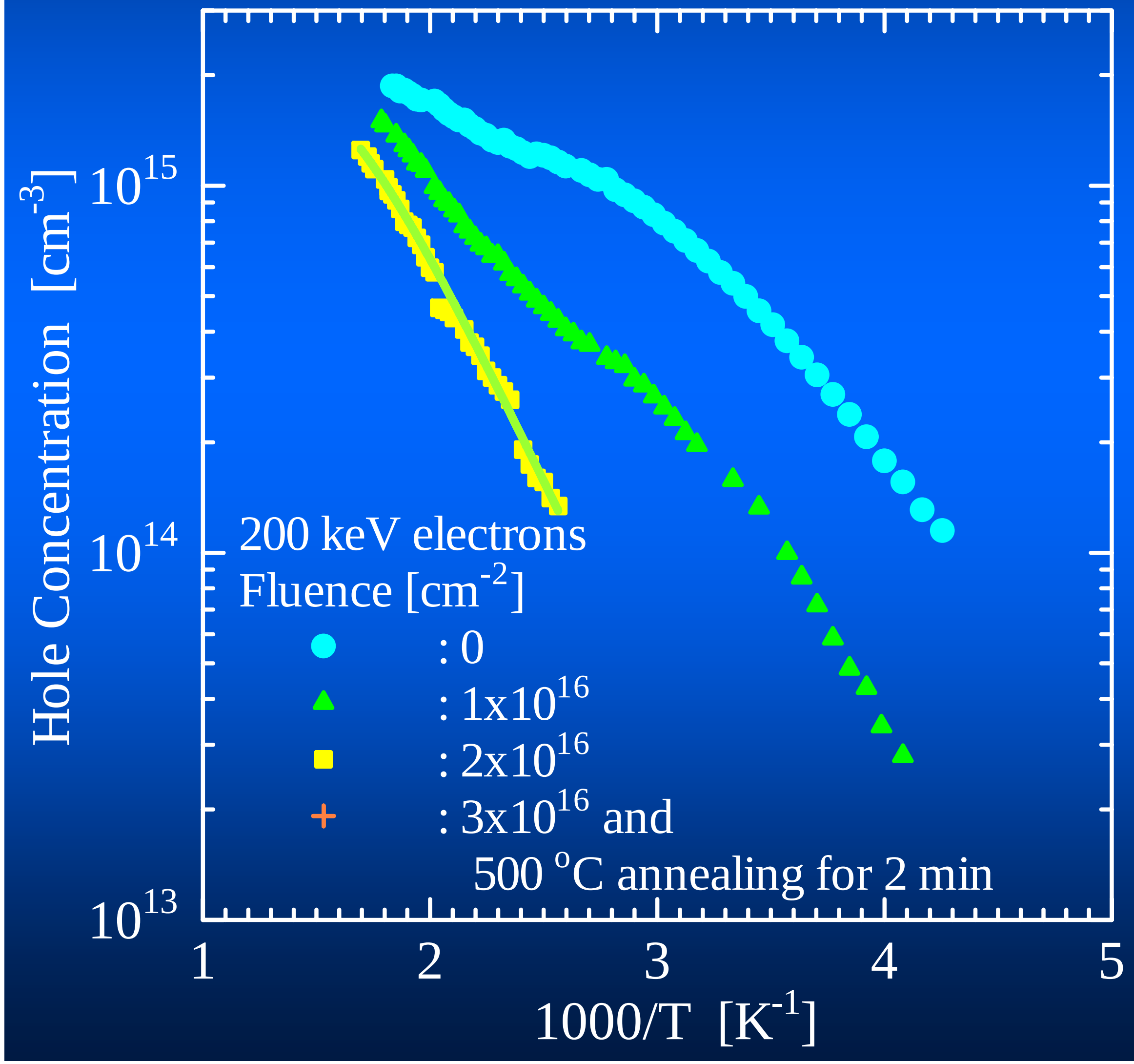
$E_{Al} = E_V + 0.27 eV$

$N_{DA} = 2.2\times10^{15} cm^{-3}$

$E_{DA} = E_V + 0.44 eV$

$N_{comp} = 1.1\times10^{14} cm^{-3}$

Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



Fluence [cm^{-2}]

2×10^{16}

Simulation Result

$N_{\mathrm{Al}} < 1\times10^{14}\mathrm{cm}^{-3}\ \mathrm{cm}^{-3}$

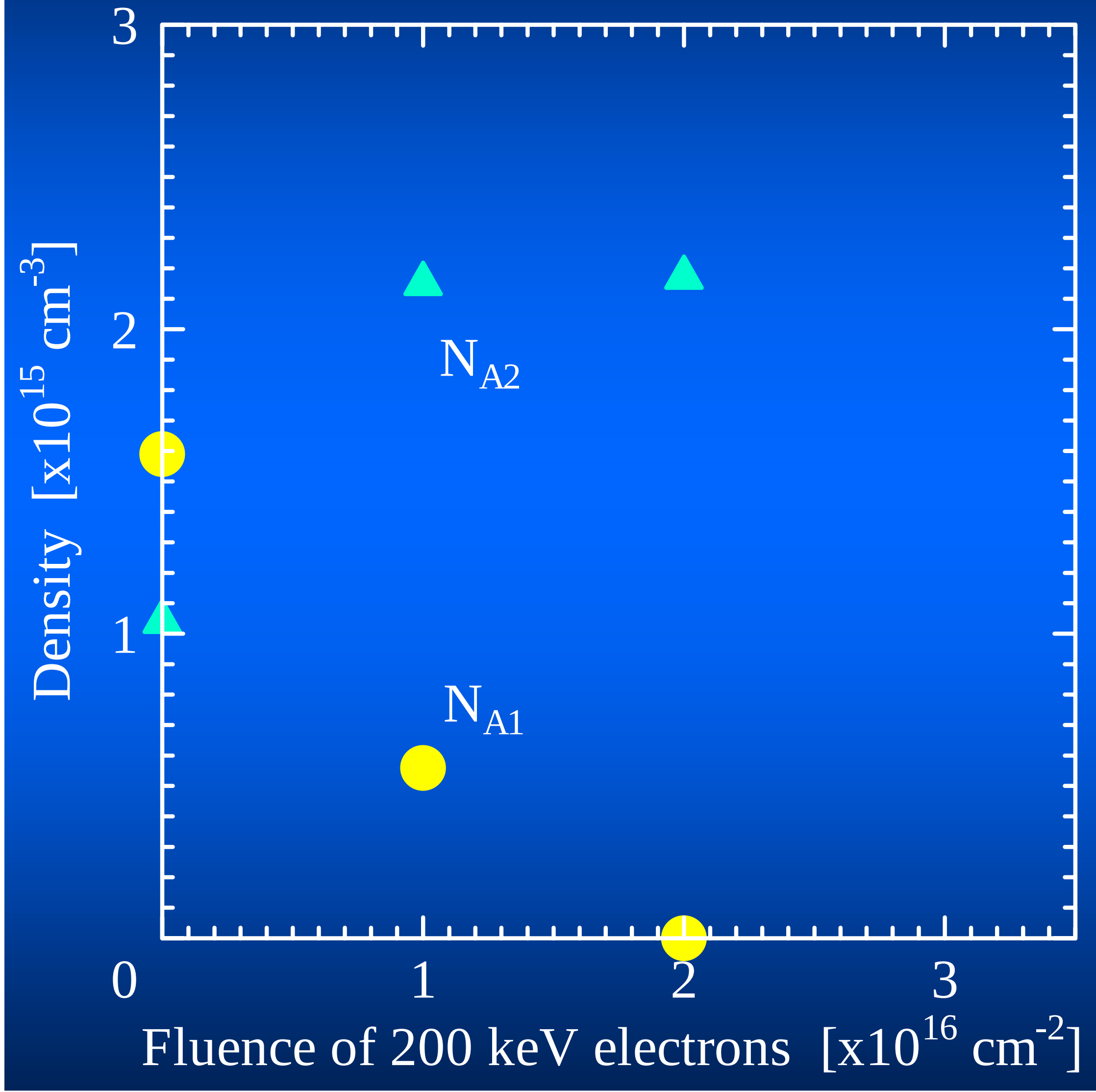
$E_{\mathrm{Al}} = E_{\mathrm{V}} + 0.24\ \mathrm{eV}$

$N_{\mathrm{DA}} = 2.2\times10^{15}\mathrm{cm}^{-3}$

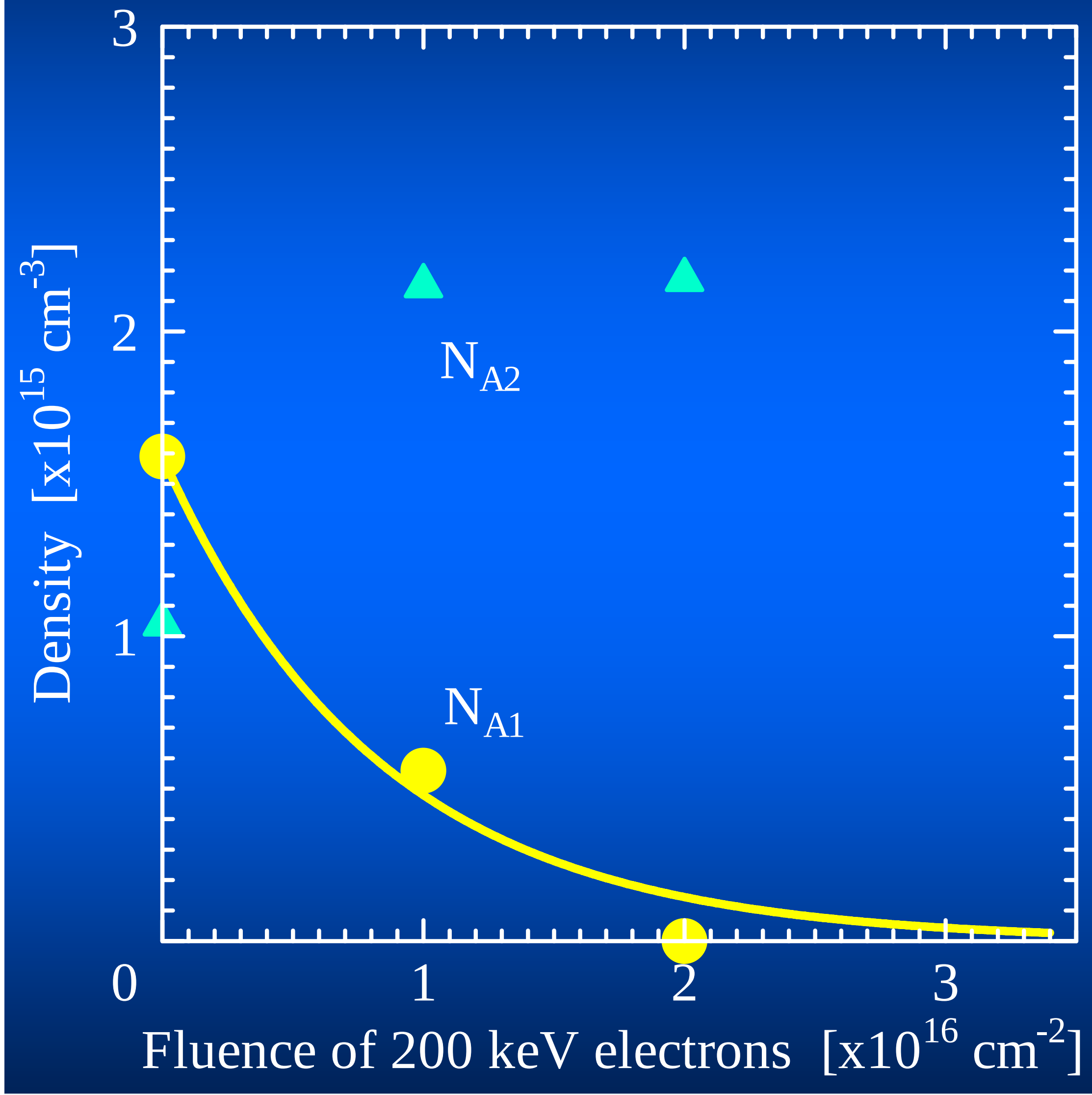
$E_{\mathrm{DA}} = E_{\mathrm{V}} + 0.47\ \mathrm{eV}$

$N_{\mathrm{comp}} = 1.1\times10^{12}\mathrm{cm}^{-3}$

Fluence Dependence of N_{Al} and N_{DA} in 6H-SiC



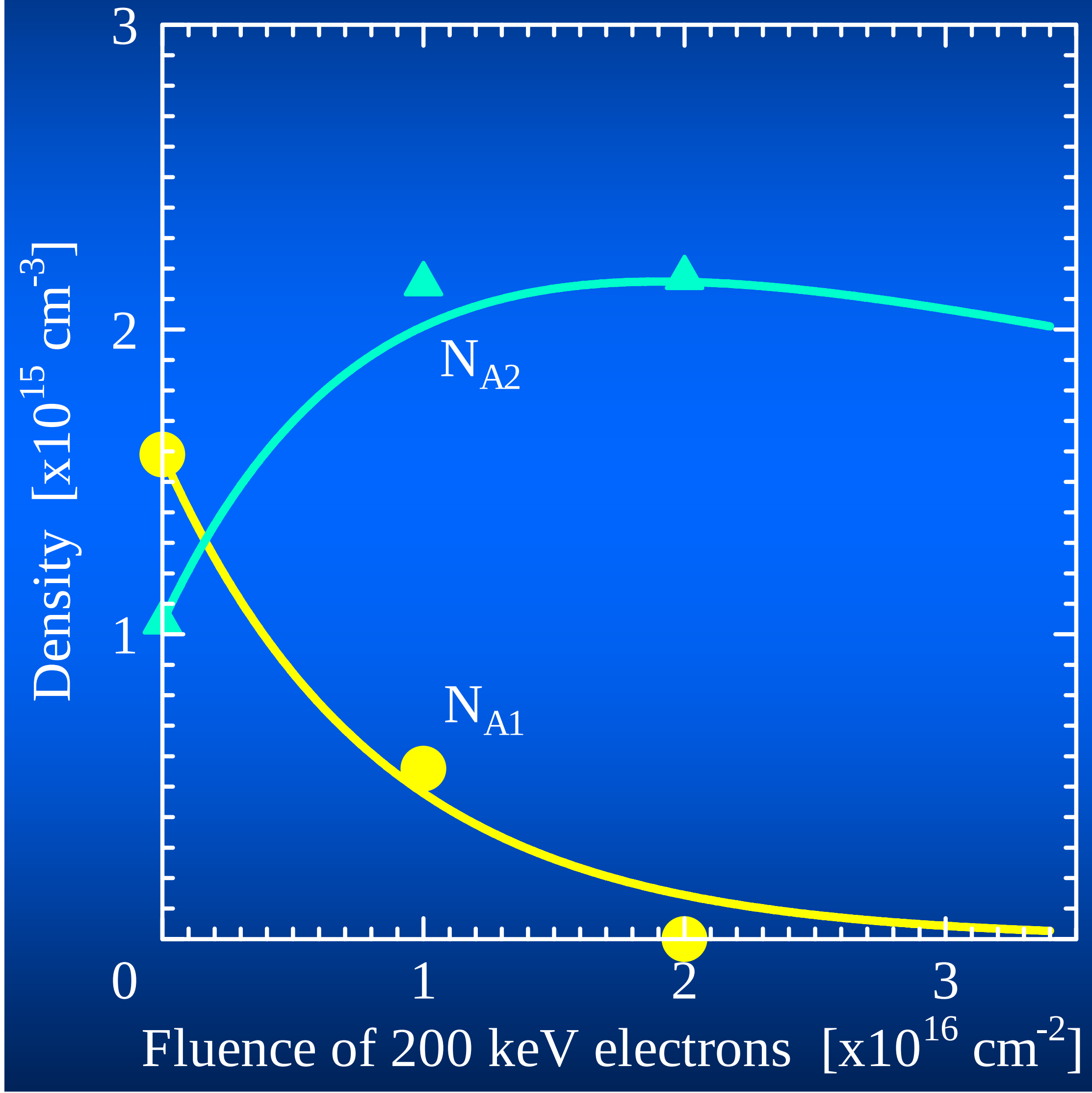
Fluence Dependence of N_{Al} and N_{DA} in 6H-SiC



$$\frac{\mathrm{d}N_{\mathrm{Al}}(\Phi)}{\mathrm{d}\Phi} = -\kappa_{\mathrm{Al}} N_{\mathrm{Al}}(\Phi)$$

$$\kappa_{\mathrm{Al}} = 1\times 10^{-16}\ \ \mathrm{cm}^2$$

Fluence Dependence of N_{Al} and N_{DA} in 6H-SiC



$$\frac{\mathrm{d}N_{Al}(\Phi)}{\mathrm{d}\Phi} = -\kappa_{Al} N_{Al}(\Phi)$$

$$\kappa_{Al} = 4.4\times10^{-17} \ \ \mathrm{cm}^2$$

$$\frac{\mathrm{d}N_{DA}(\Phi)}{\mathrm{d}\Phi} = -\frac{\mathrm{d}N_{Al}(\Phi)}{\mathrm{d}\Phi} - \kappa_{DA} N_{DA}(\Phi)$$

$$\kappa_{DA} = 9\times10^{-18} \ \ \mathrm{cm}^2$$

Comparison of removal cross sections for Al-doped 4H-SiC and 6H-SiC by 200 keV electron irradiation

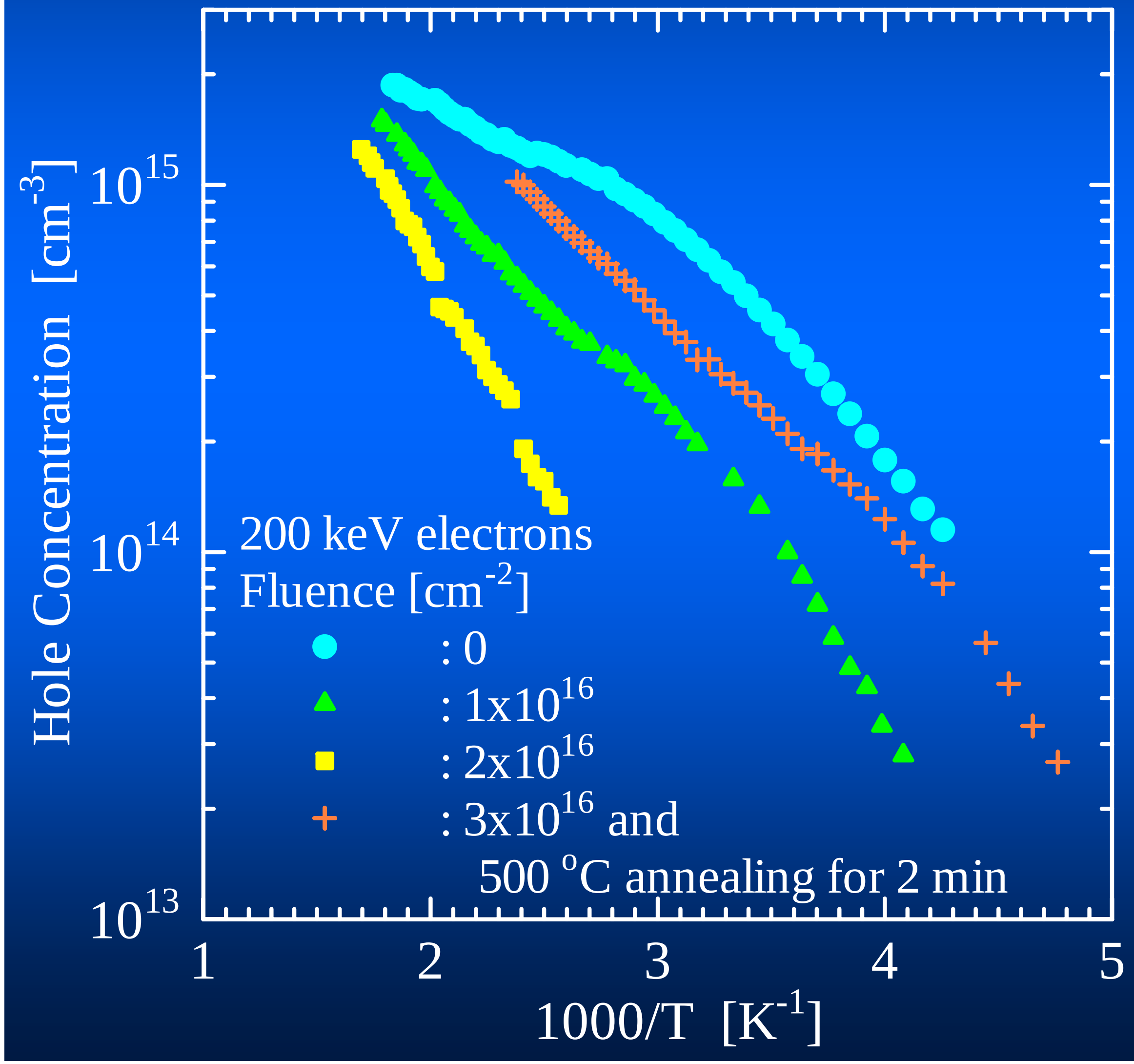
	Al-doped 6H-SiC	Al-doped 4H-SiC
κ_{Al} [cm^2]	1×10^{-16}	4.4×10^{-17}
κ_{DA} [cm^2]	9×10^{-18}	1.0×10^{-17}

κ_{Al} for 6H-SiC is larger than that for 4H-SiC

⇩

Al-doped 6H-SiC is radiation-resistant less than Al-doped 4H-SiC

Reduction in p(T) in Al-doped p-type 6H-SiC by 200 keV electron irradiation



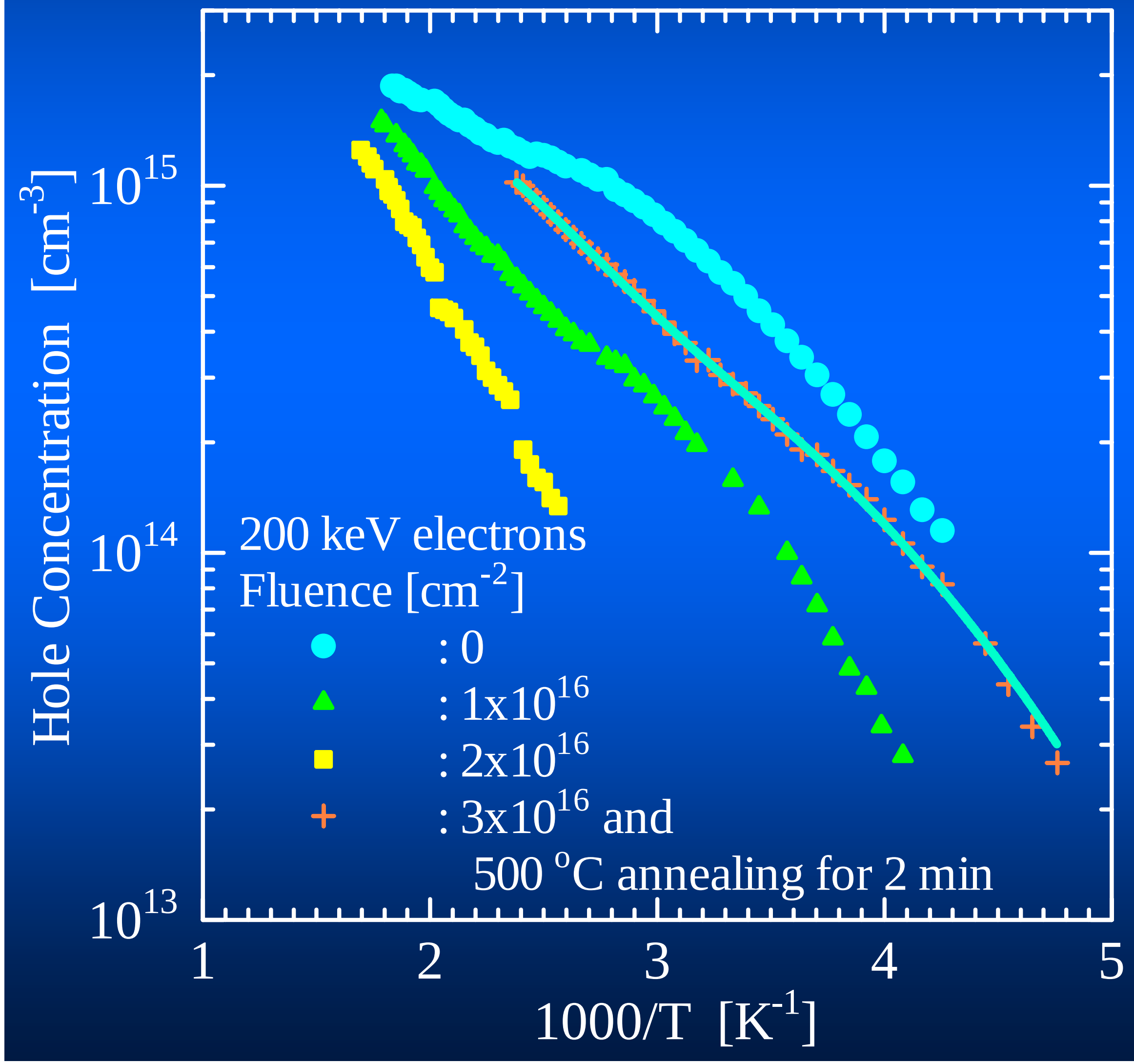
Fluence [cm^{-2}]

3×10^{16}

The sample irradiated by 3x10^{16} cm^{-2} fluence could not be measured.

Therefore, the sample was annealed at 500 ^{o}C for 2 min.

Recovery in p(T) in Al-doped p-type 6H-SiC by 500 °C annealing



Fluence: 3×10^{16} cm^{-2}

Annealing: 500 °C

2 min

Simulation Result

$$N_{\mathrm{Al}} = 4.0\times10^{15}\mathrm{cm}^{-3}$$

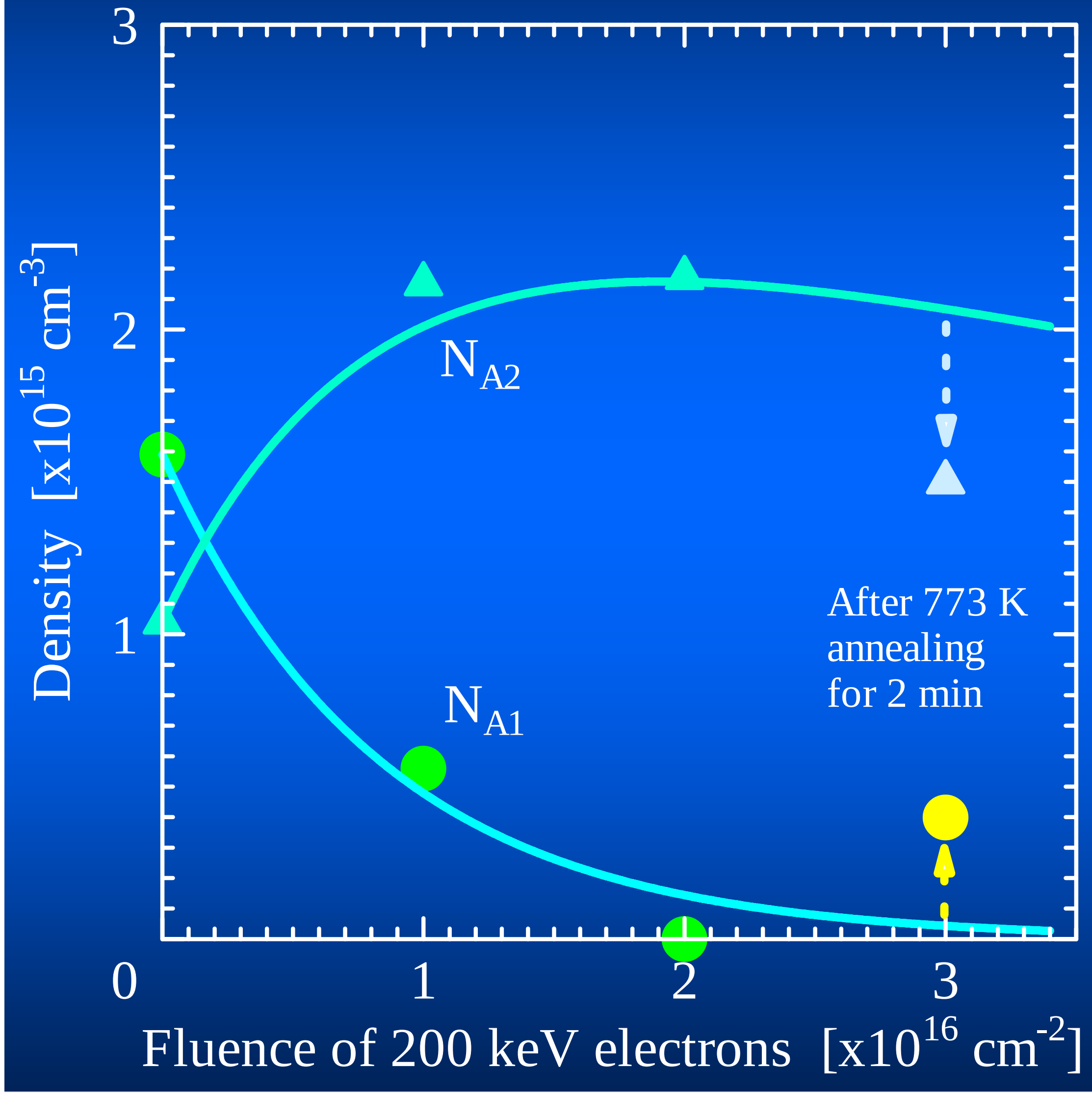
$$E_{\mathrm{Al}} = E_{\mathrm{V}} + 0.23\ \mathrm{eV}$$

$$N_{\mathrm{DA}} = 1.5\times10^{15}\mathrm{cm}^{-3}$$

$$E_{\mathrm{DA}} = E_{\mathrm{V}} + 0.34\ \mathrm{eV}$$

$$N_{\mathrm{comp}} = 6.6\times10^{13}\mathrm{cm}^{-3}$$

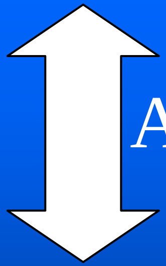
Fluence Dependence of N_{Al} and N_{DA} in 6H-SiC



500 °C Annealing for 2 min

Increment of N_{Al}:

4×10^{14} cm^{-3}

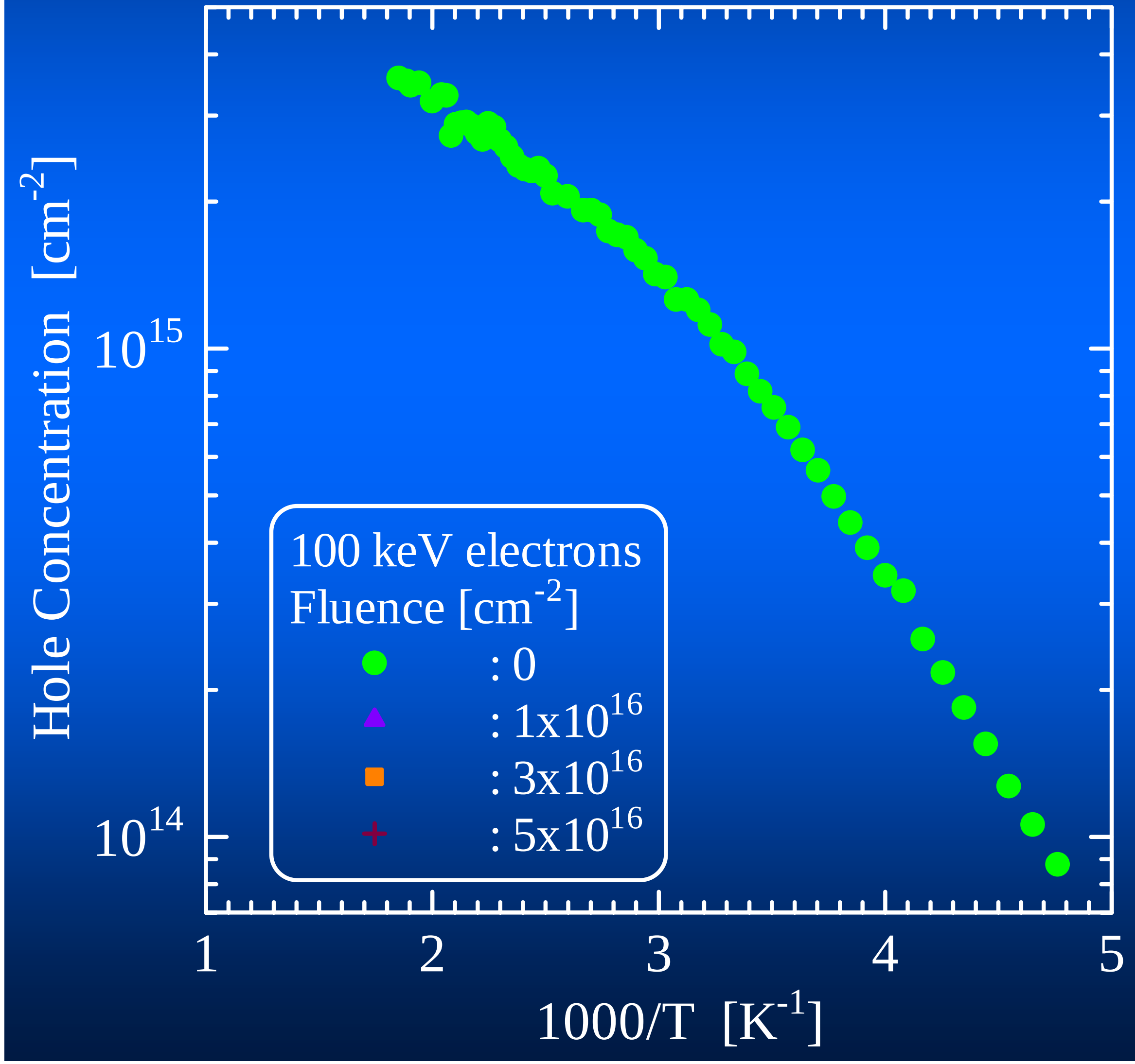


Almost the same

Decrement of N_{DA}:

6×10^{14} cm^{-3}

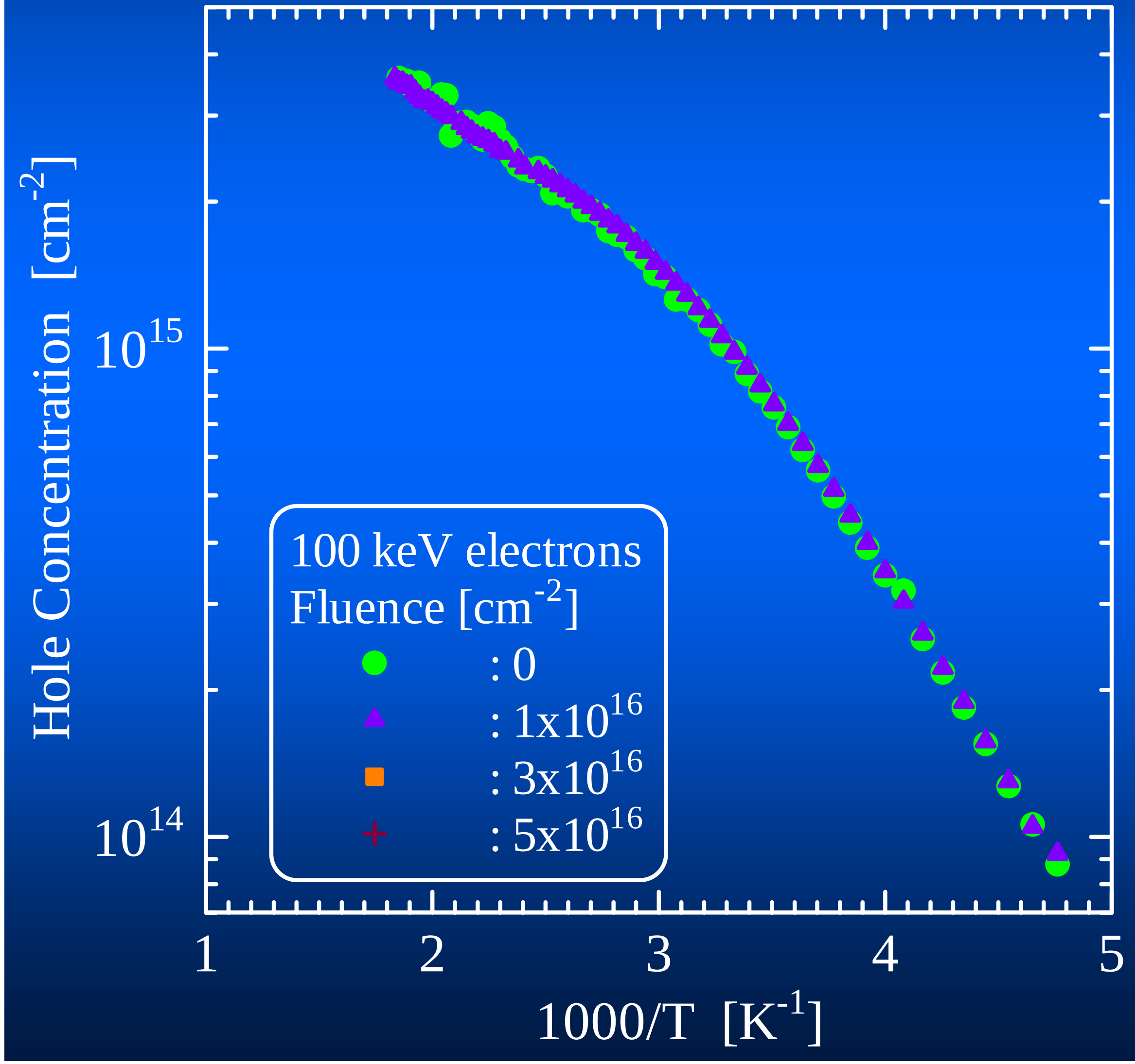
Reduction in p(T) in Al-doped p-type 6H-SiC by **100 keV** electron irradiation



Fluence [cm^{-2}]

0

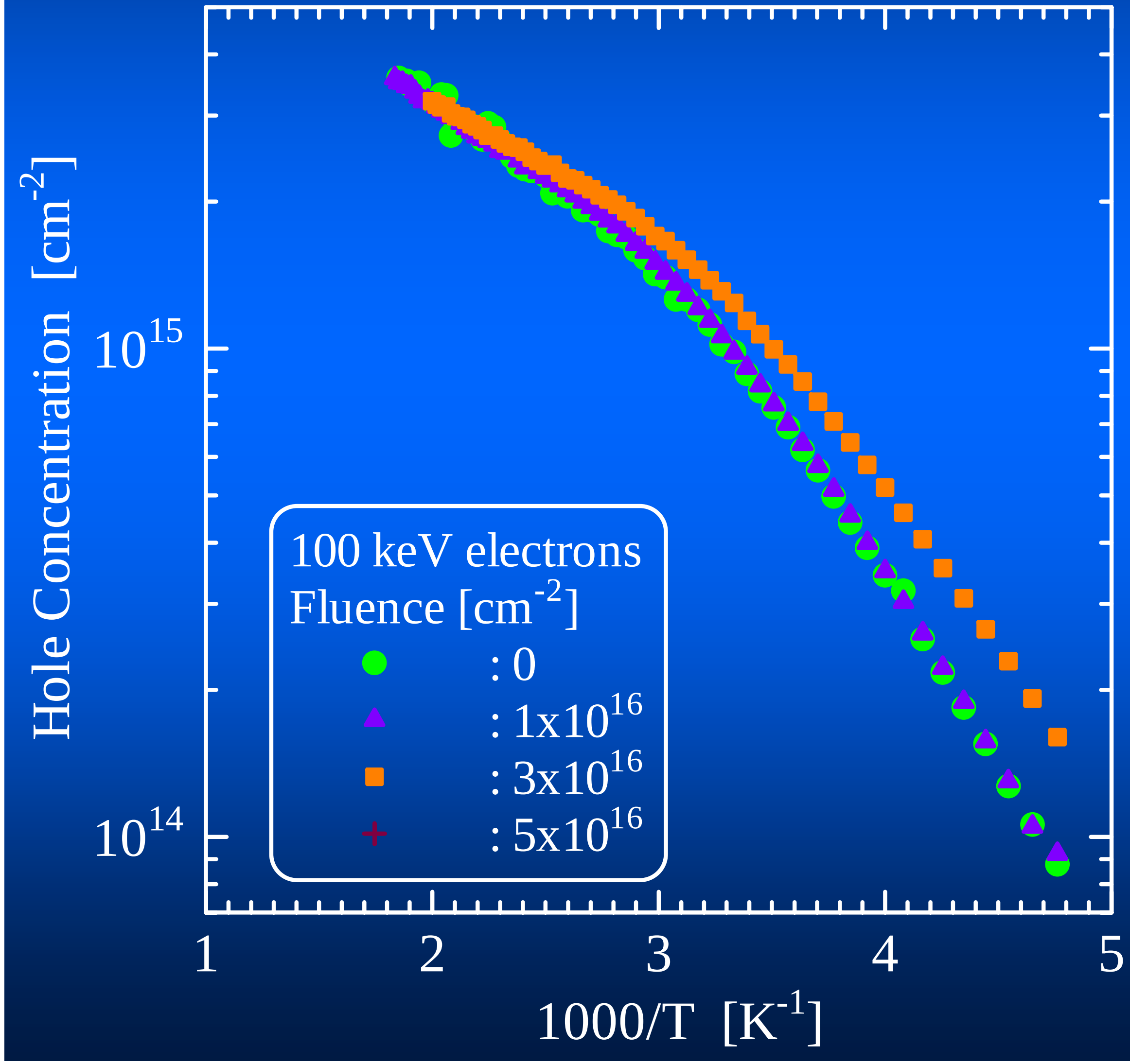
Reduction in p(T) in Al-doped p-type 6H-SiC by **100 keV** electron irradiation



Fluence [cm^{-2}]

1×10^{16}

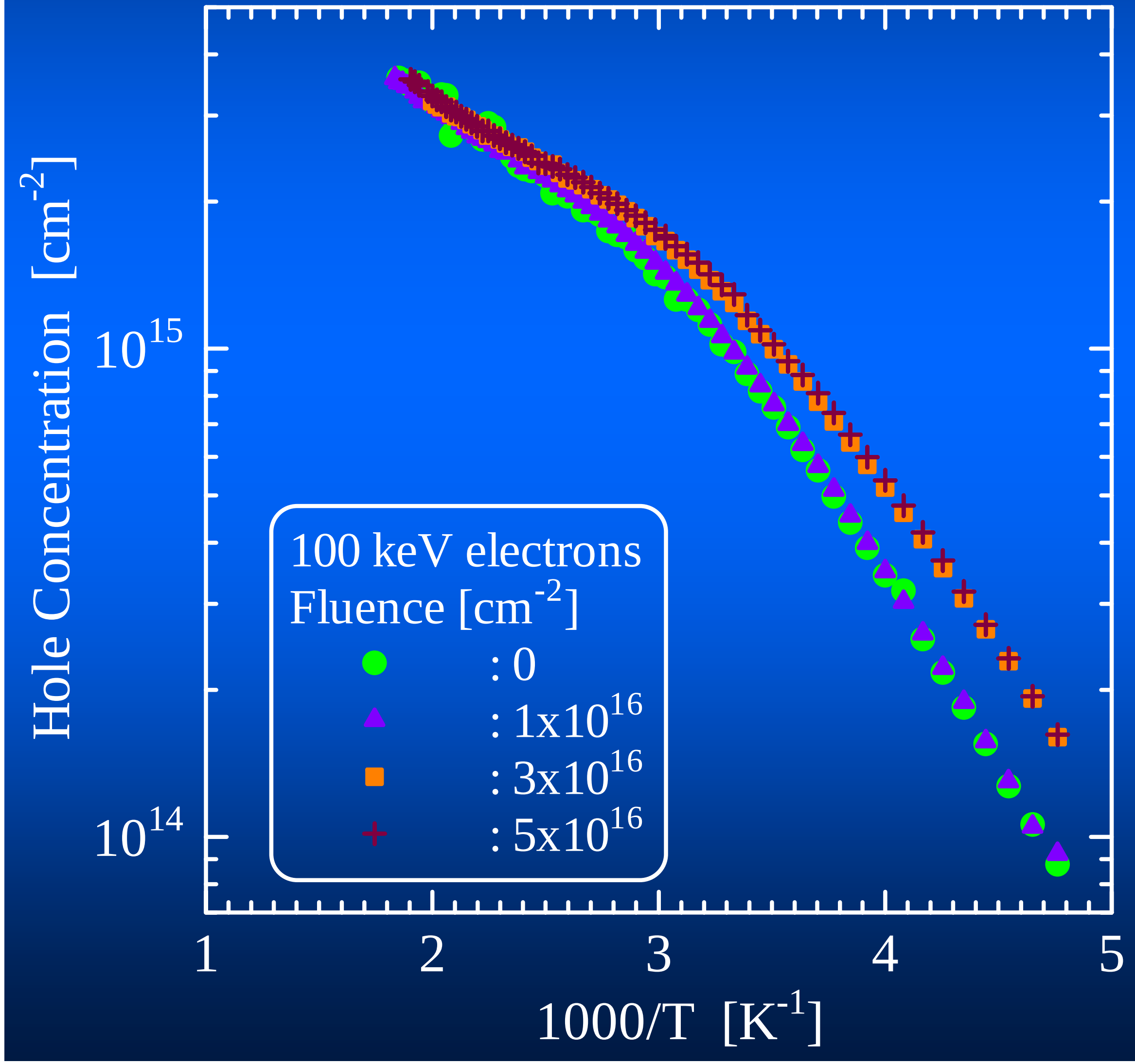
Reduction in p(T) in Al-doped p-type 6H-SiC by **100 keV** electron irradiation



Fluence [cm^{-2}]

3×10^{16}

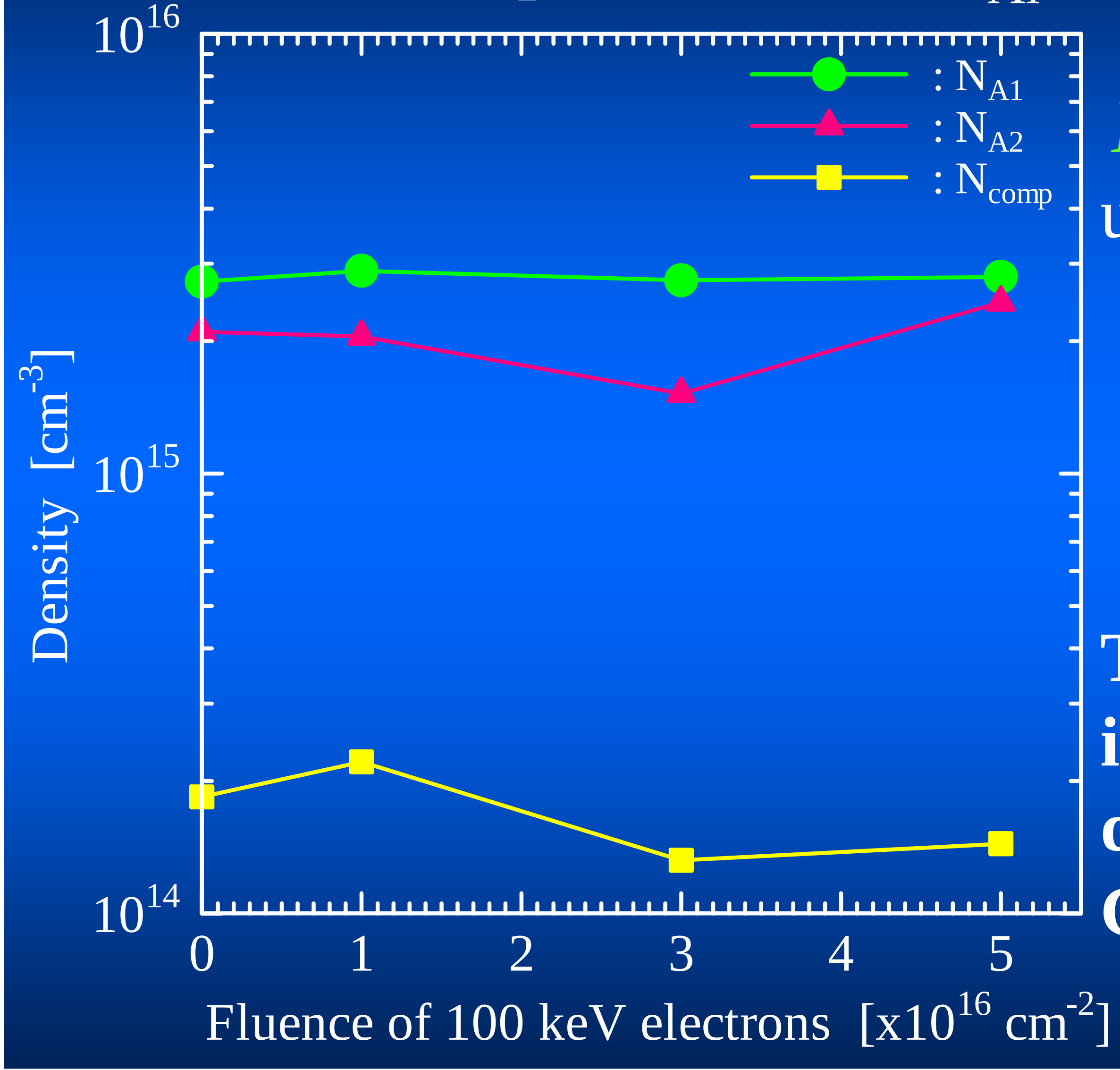
Reduction in p(T) in Al-doped p-type 6H-SiC by **100 keV** electron irradiation



Fluence [cm^{-2}]

5×10^{16}

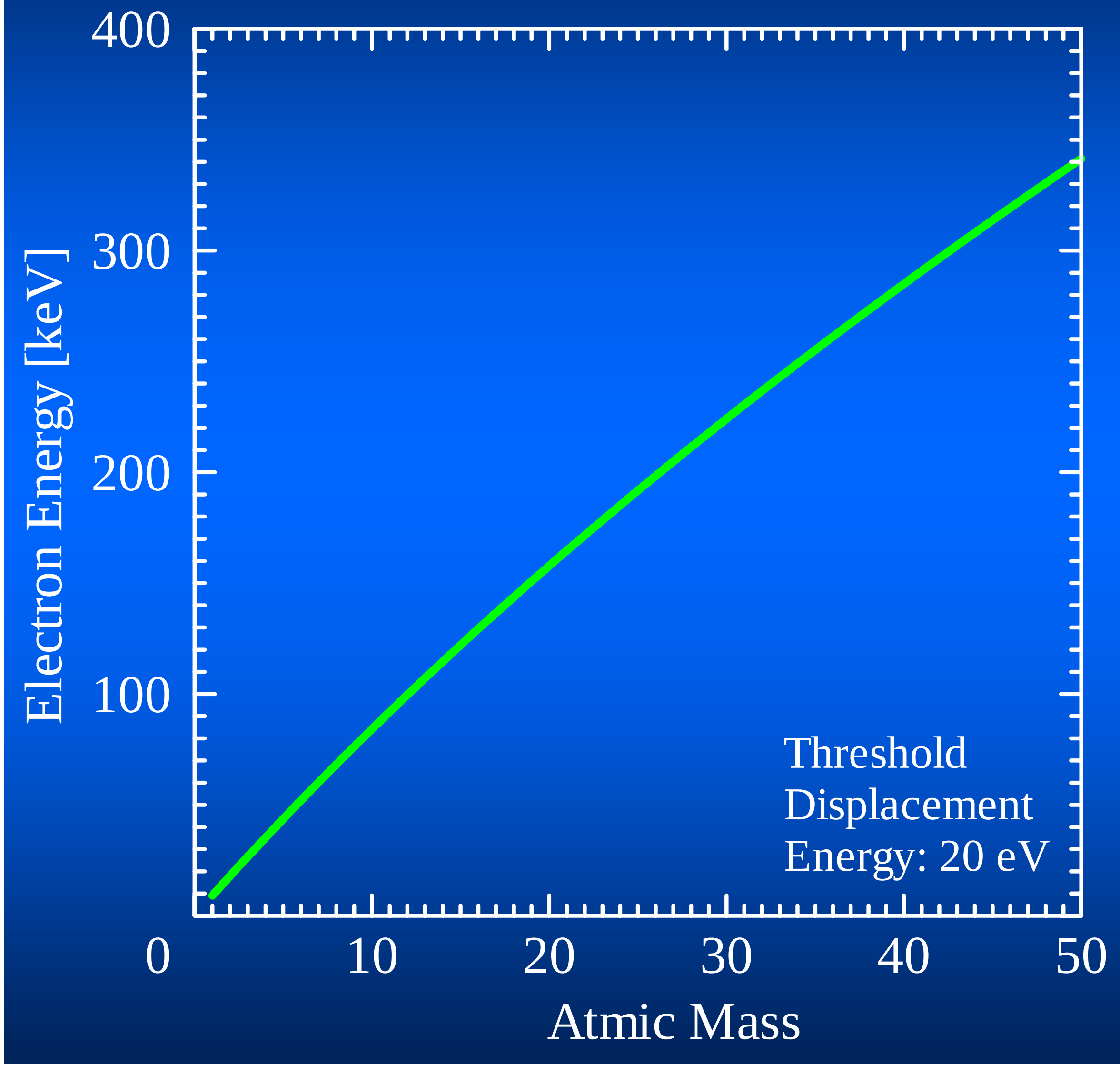
Fluence Dependence of N_{Al} and N_{DA} in 6H-SiC



N_{Al} and N_{DA} are almost unchanged.

The 100 keV electron irradiation cannot displace substitutional C.

Minimum Electron Energy for displacement of Substitutional Atom



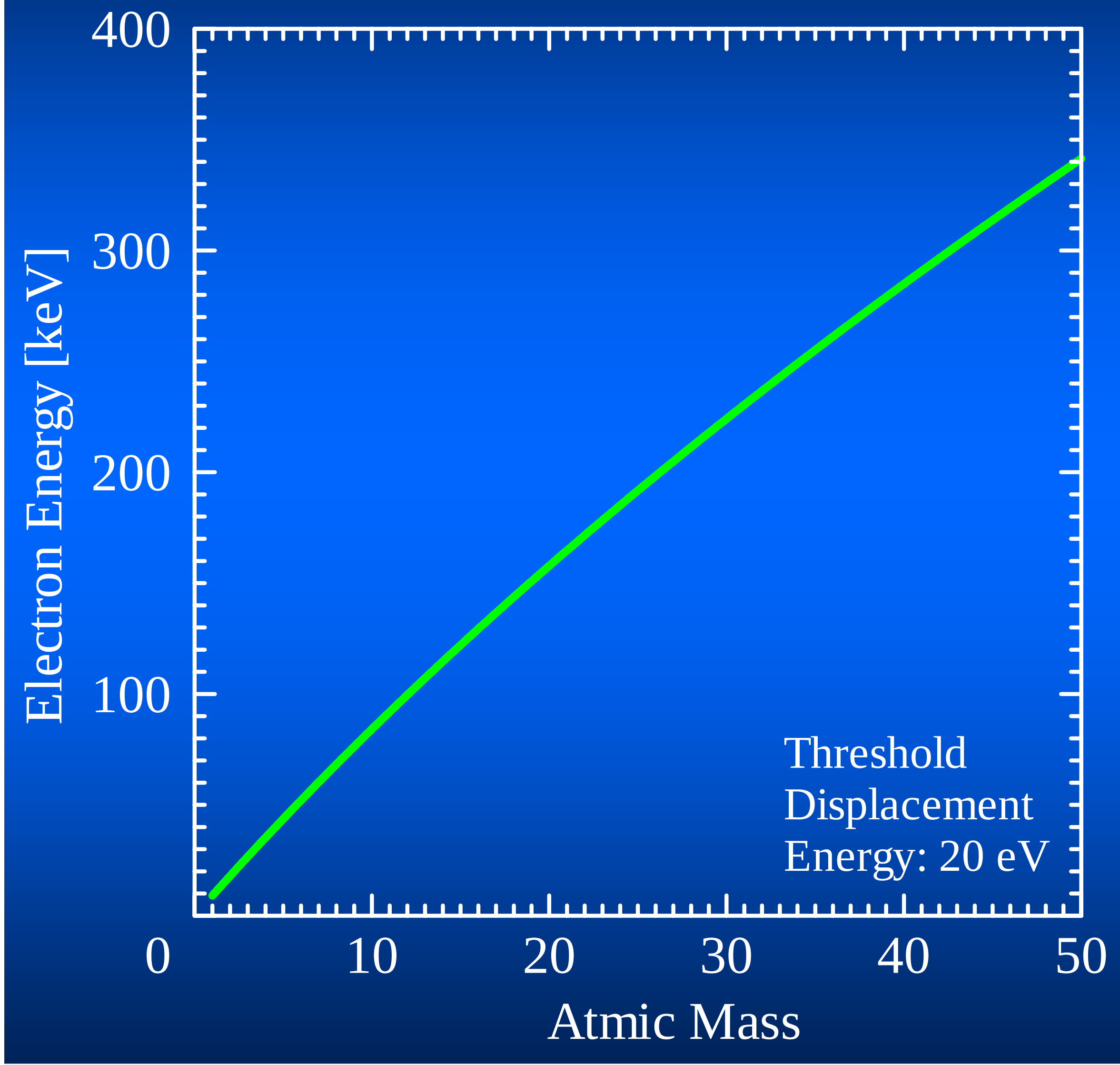
Head-on collision

An electron having E keV

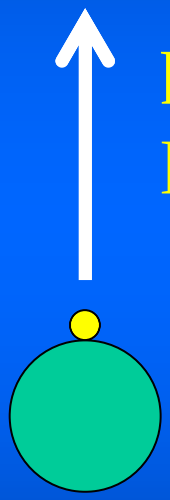
Atom

Threshold displacement energy: E_d eV

Minimum Electron Energy for displacement of Substitutional Atom



Head-on collision

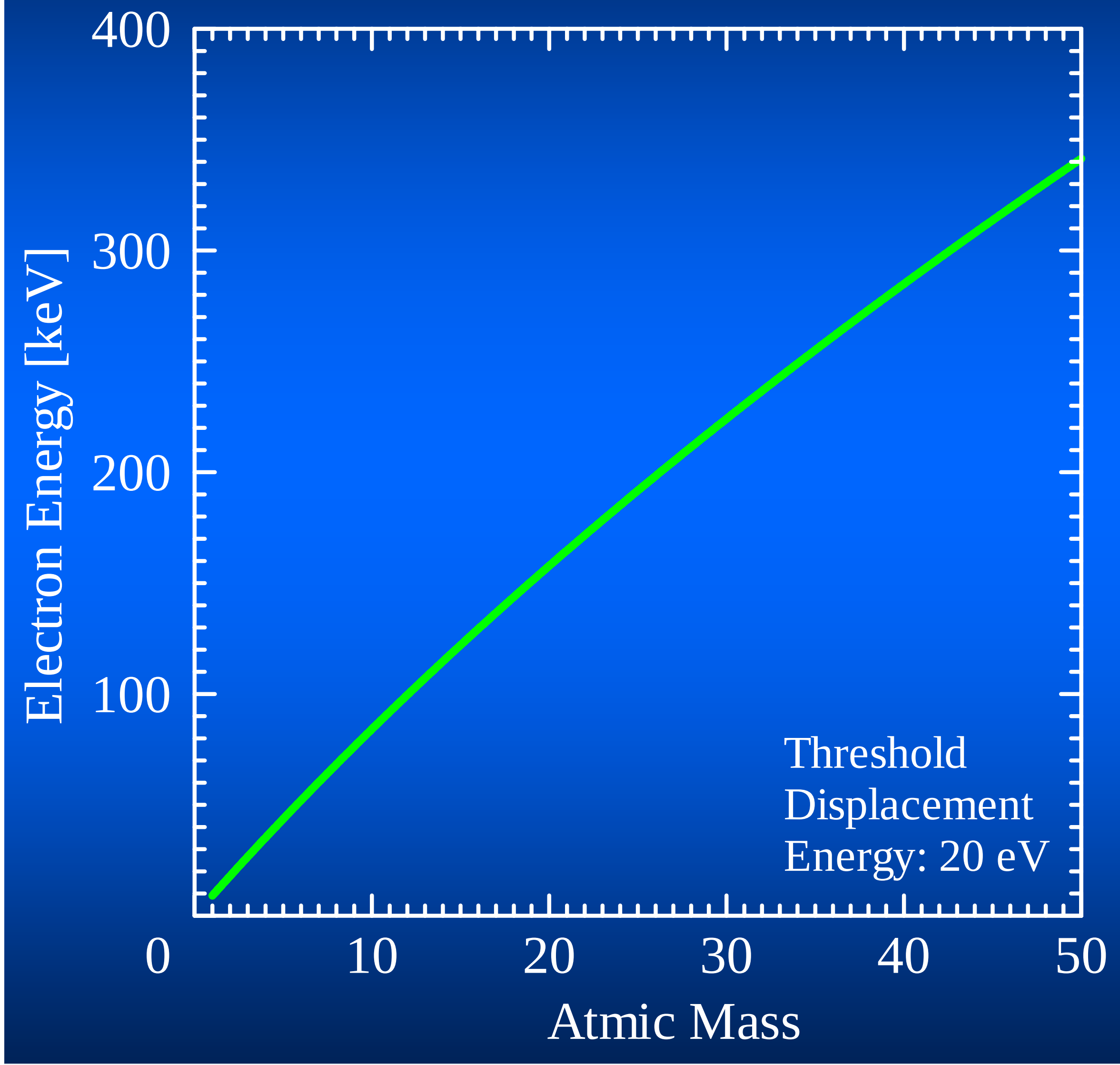


The electron having E keV loses energy of α eV

If $\alpha \geq E_d$

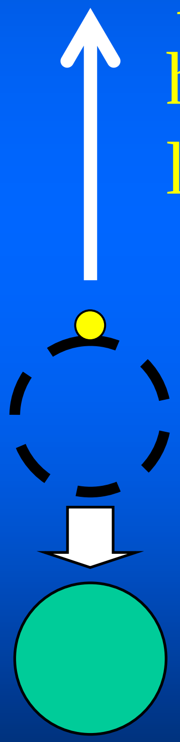
Threshold displacement energy: E_d eV

Minimum Electron Energy for displacement of Substitutional Atom



Threshold Displacement Energy: 20 eV

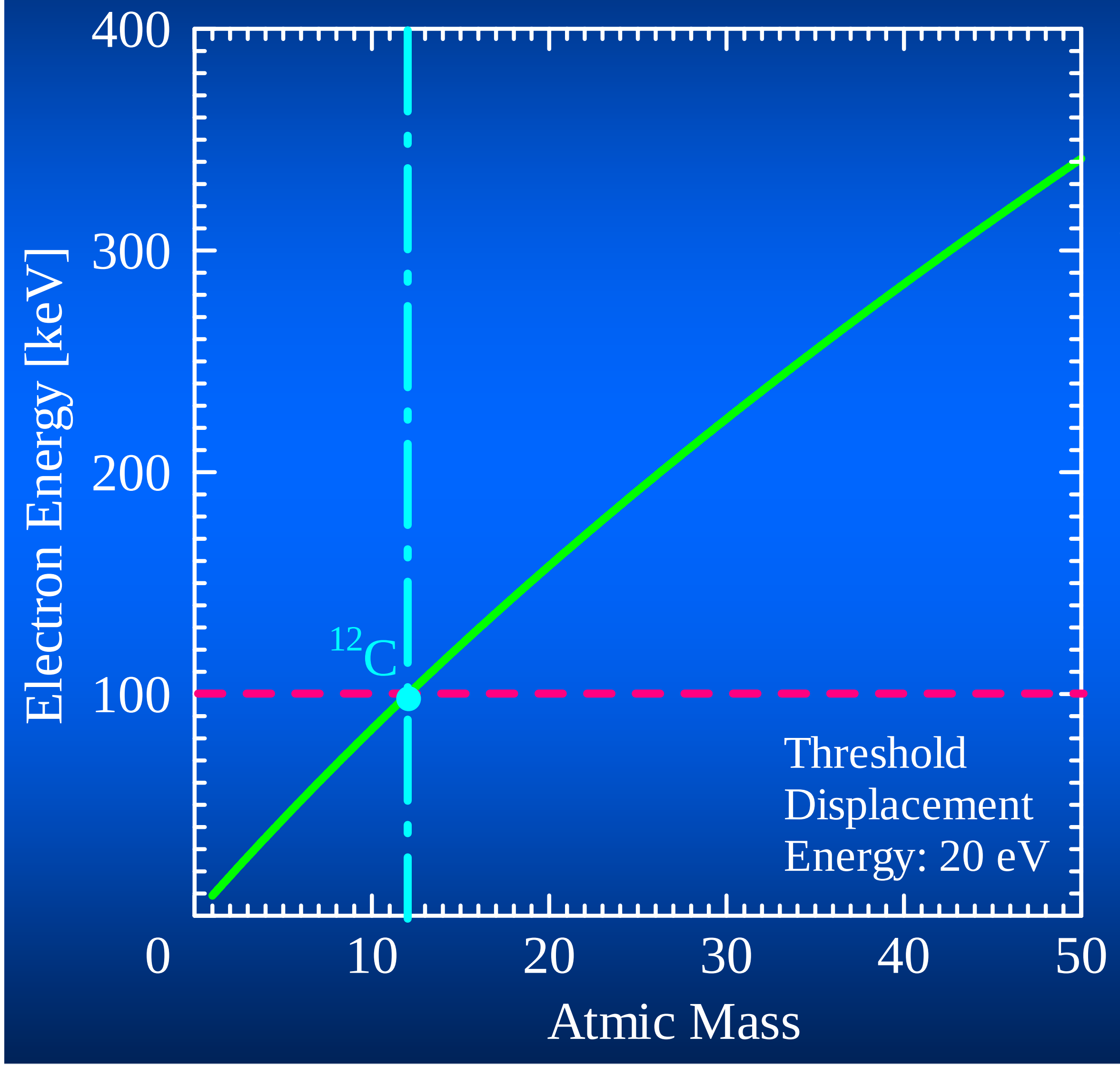
Head-on collision



The electron having E keV loses energy of α eV

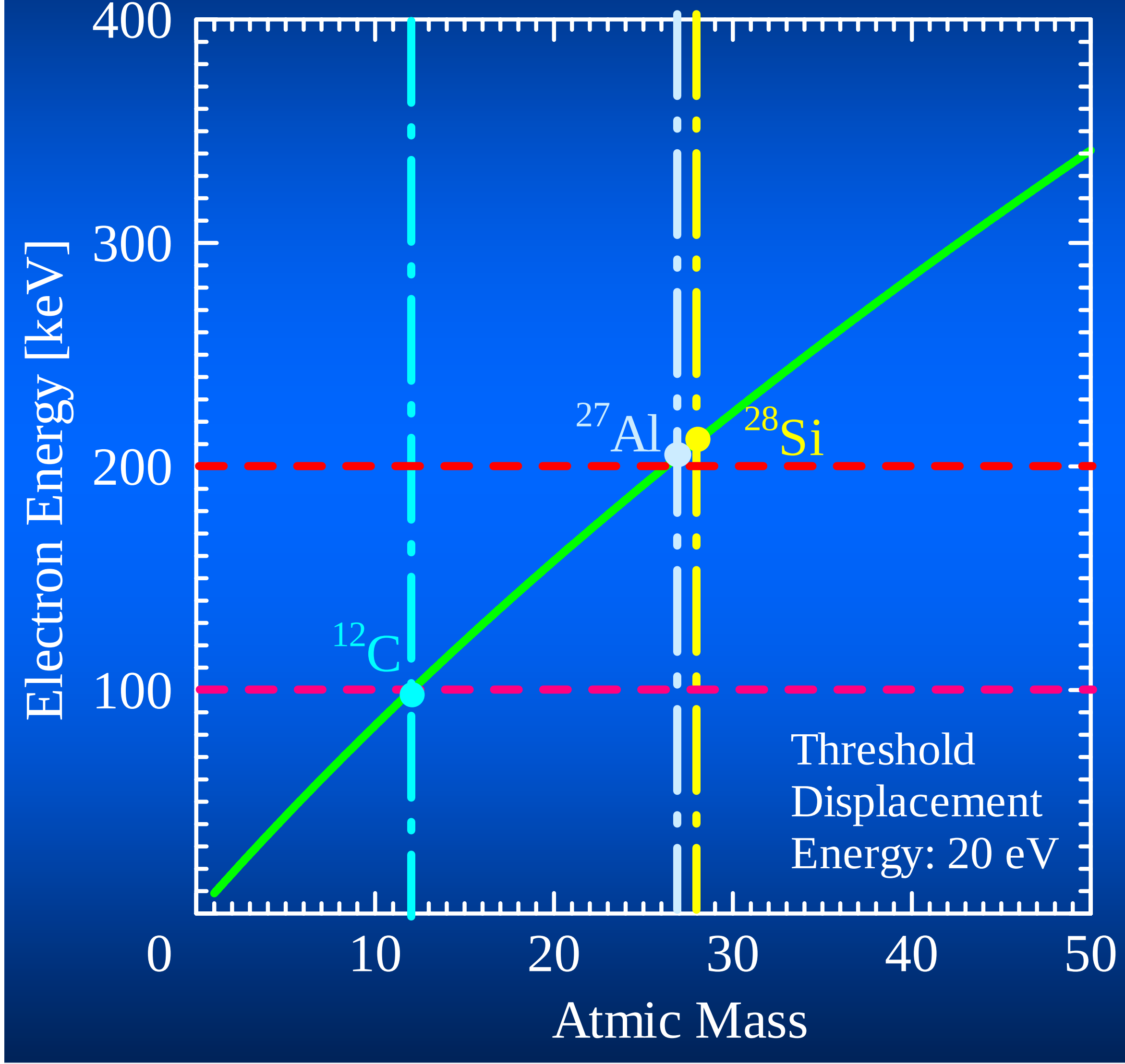
If $\alpha \geq E_d$ the atom is displaced.

Minimum Electron Energy for displacement of Substitutional Atom

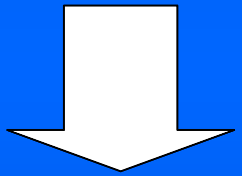


In the case of E_d=20 eV, the substitutional C can be displaced by 100 keV electron irradiation.

Minimum Electron Energy for displacement of Substitutional Atom

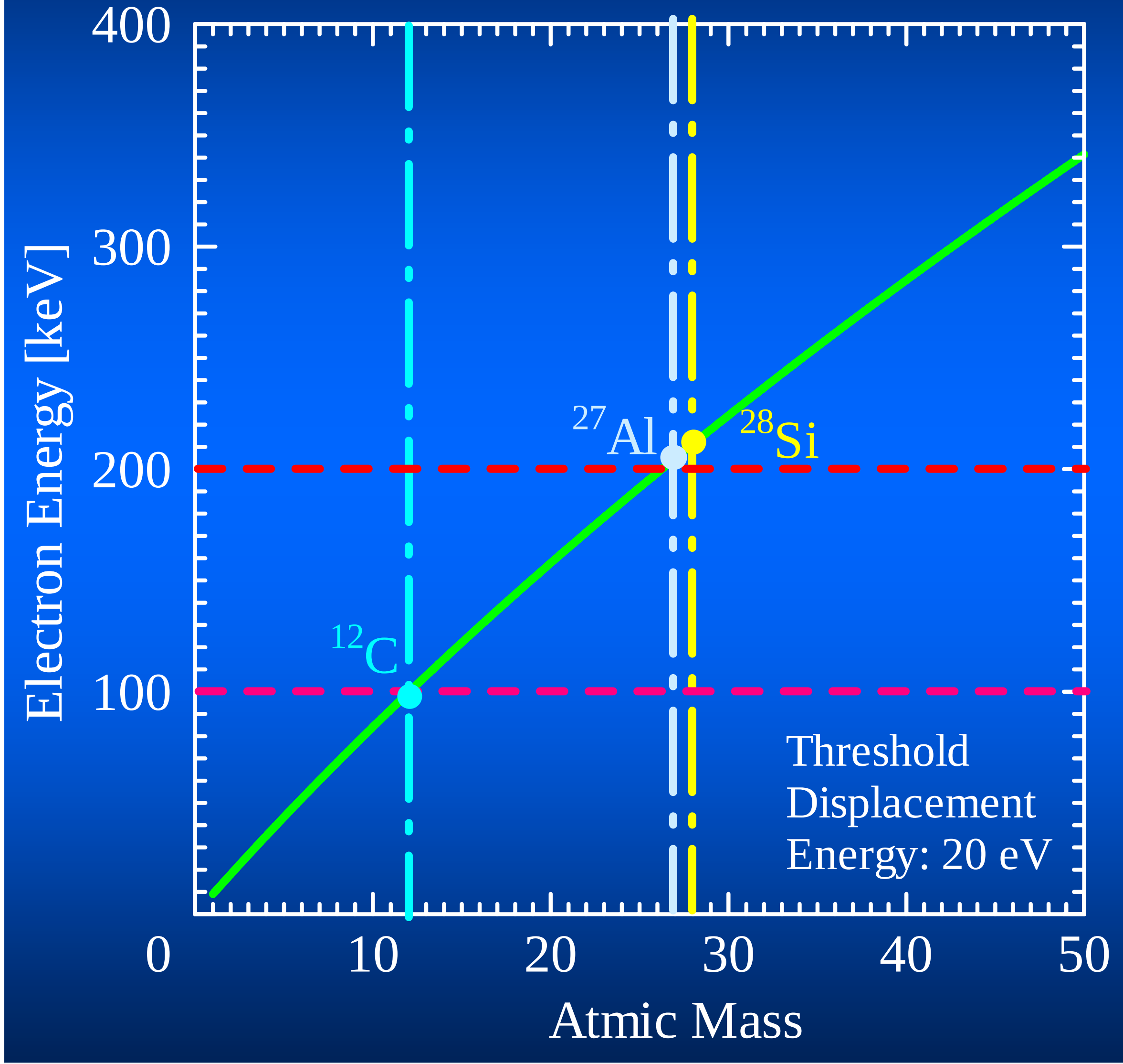


In the case of E_d=20 eV, the substitutional C can be displaced by 100 keV electron irradiation.

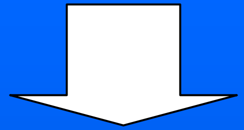


However, substitutional Al and Si cannot be displaced.

Minimum Electron Energy for displacement of Substitutional Atom

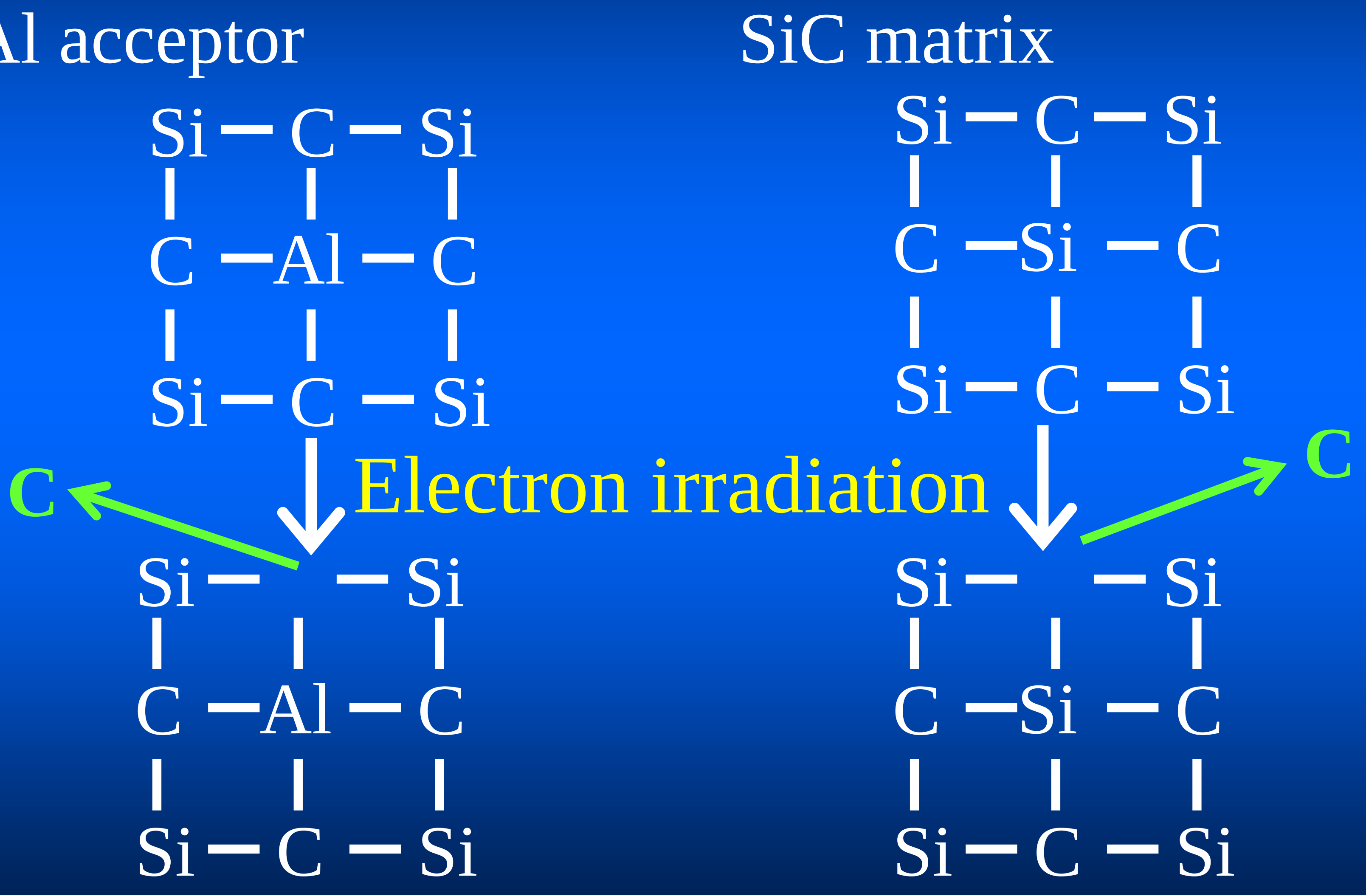


Experimentally, the 100 keV electron irradiation could not displace the substitutional C.



The 200 keV electron irradiation cannot displace the substitutional Al and Si.

Displacement of C by **200 keV** electron irradiation

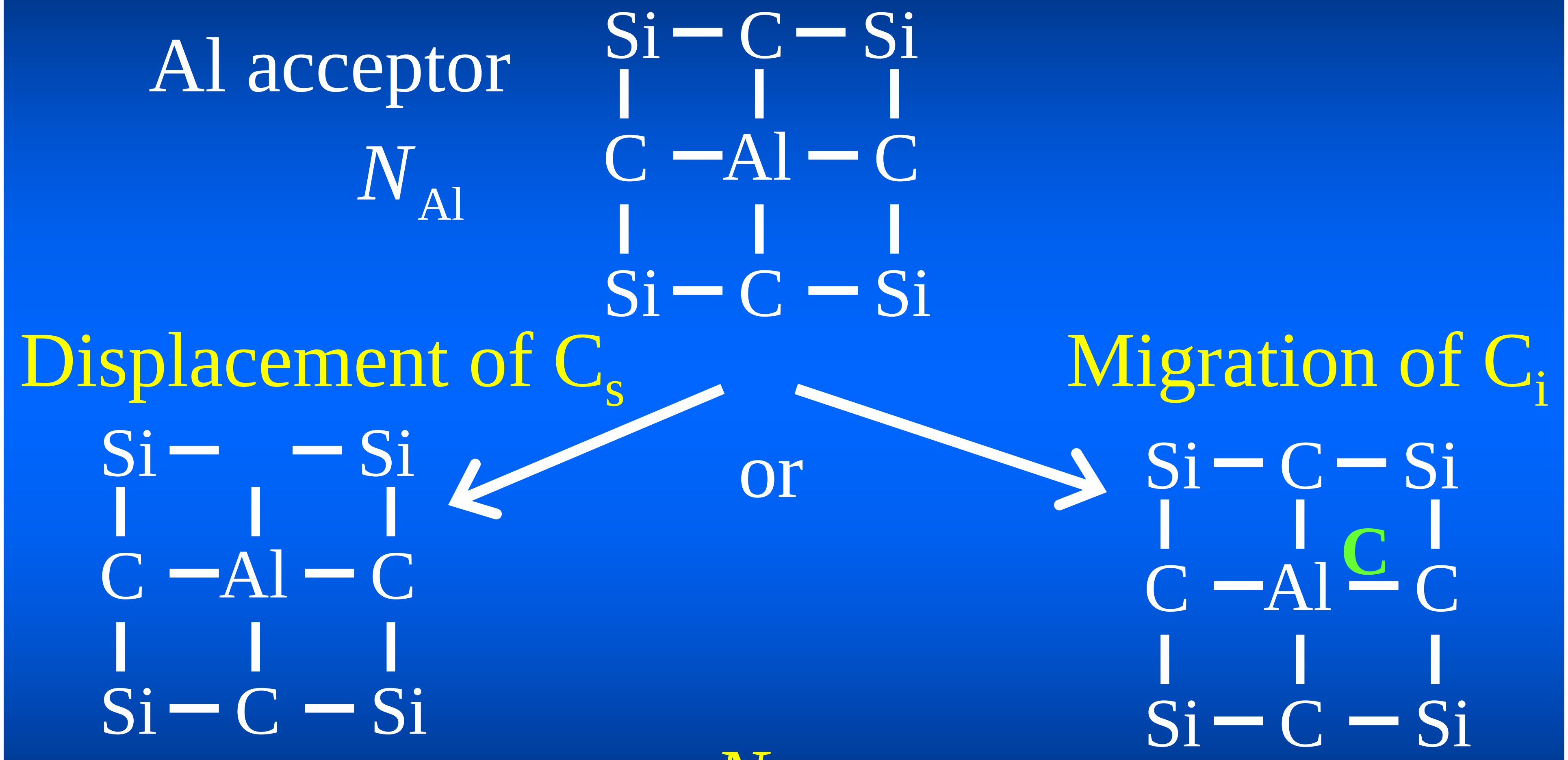


Al acceptor

SiC matrix

Electron irradiation

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



Al acceptor

N_{Al}

Si — C — Si
C — Al — C
Si — C — Si

Displacement of C_s

or

Migration of C_i

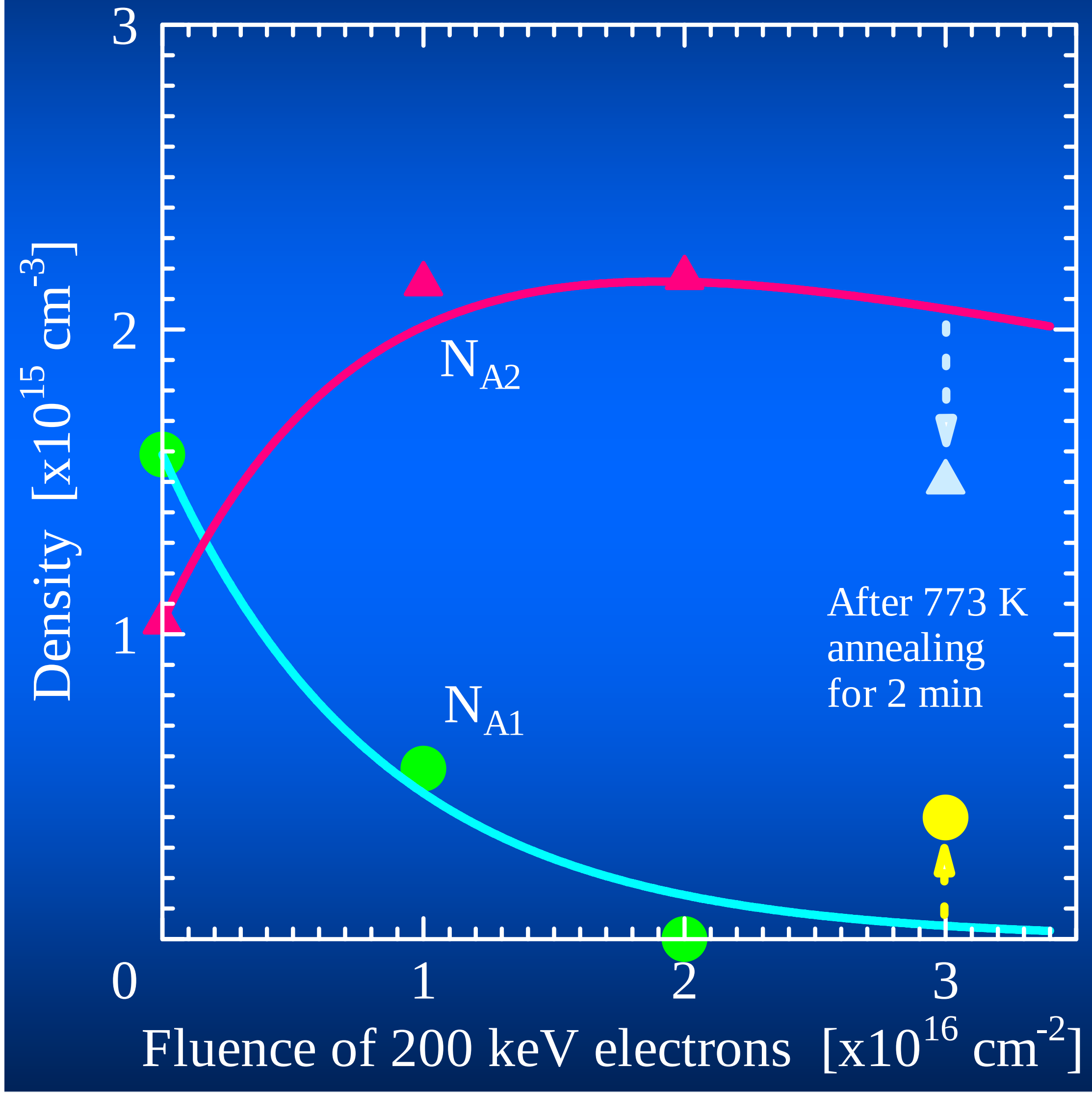
Si —   — Si
C — Al — C
Si — C — Si

Si — C — Si
C — Al C — C
Si — C — Si

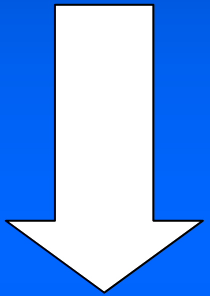
Al_{Si}-V_C complex → N_{DA} ← Al_{Si}-C_s-C_i complex

N_{Al} **decreases, whereas** N_{DA} **increases.**

Change of N_{Al} and N_{DA} in 6H-SiC by annealing

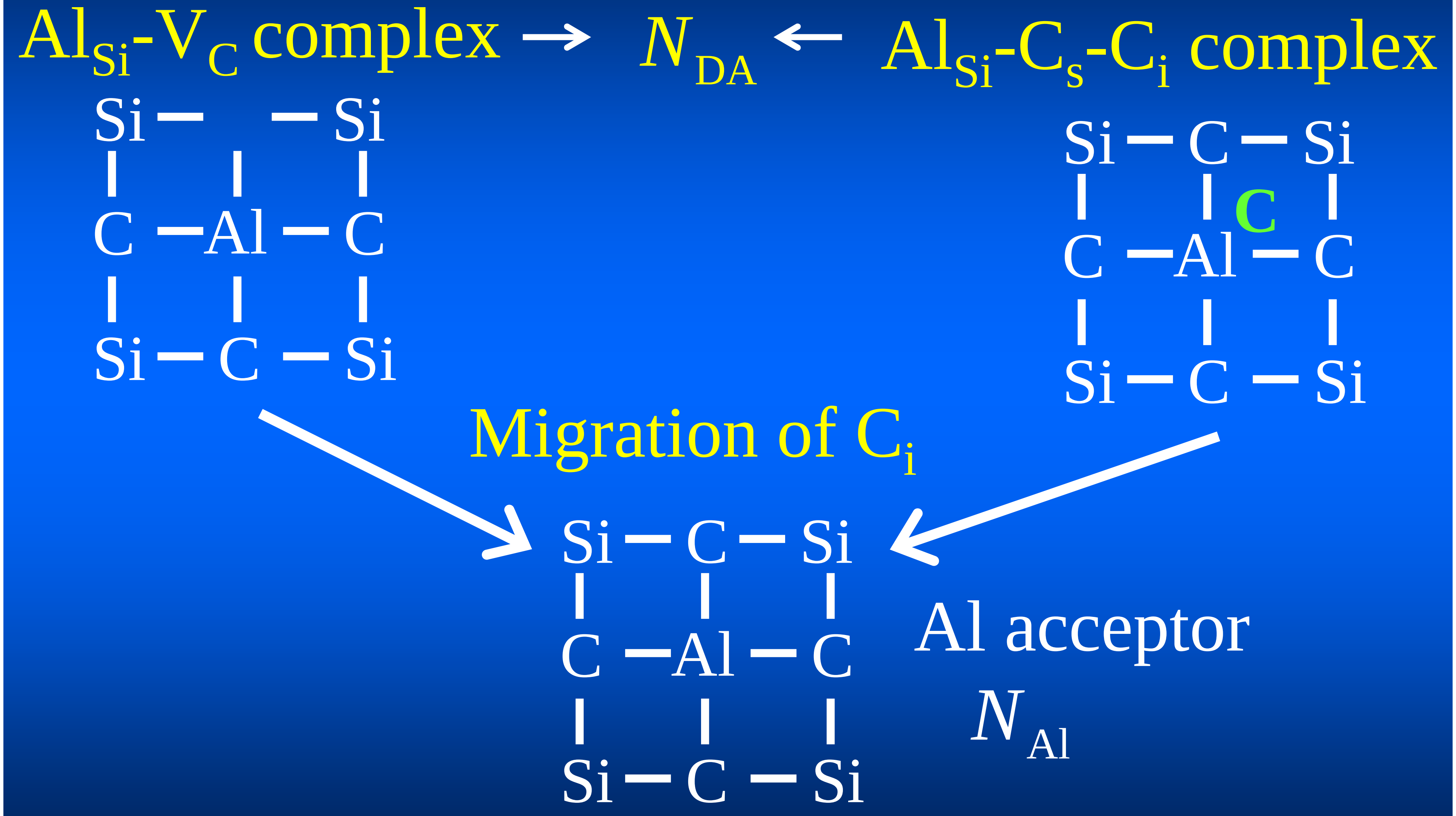


500 °C Annealing



V_C cannot migrate, whereas C_i can migrate.

The reason why the N_{Al} is increased by annealing



Al_{Si}-V_C complex → N_{DA} ← Al_{Si}-C_s-C_i complex

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

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

Migration of C_i

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

Al acceptor

N_{Al}

N_{Al} increases, whereas N_{DA} decreases.

Conclusion

1. With 200 keV electron irradiation, the Al acceptor density (N_{Al}) was decreased, while the unknown deep acceptor density (N_{DA}) was increased.
2. 200 keV electron could displace only a substitutional C into an interstitial site.
3. With 500 ºC annealing, the increment of N_{Al} was similar to the decrement of N_{DA}.
4. The deep acceptor might be an Al_{Si}-V_C complex or Al_{Si}-C_s-C_i complex.