Reduction in Majority-Carrier Concentration in N-Doped or Al-Doped 4H-SiC Epilayer by Electron Irradiation

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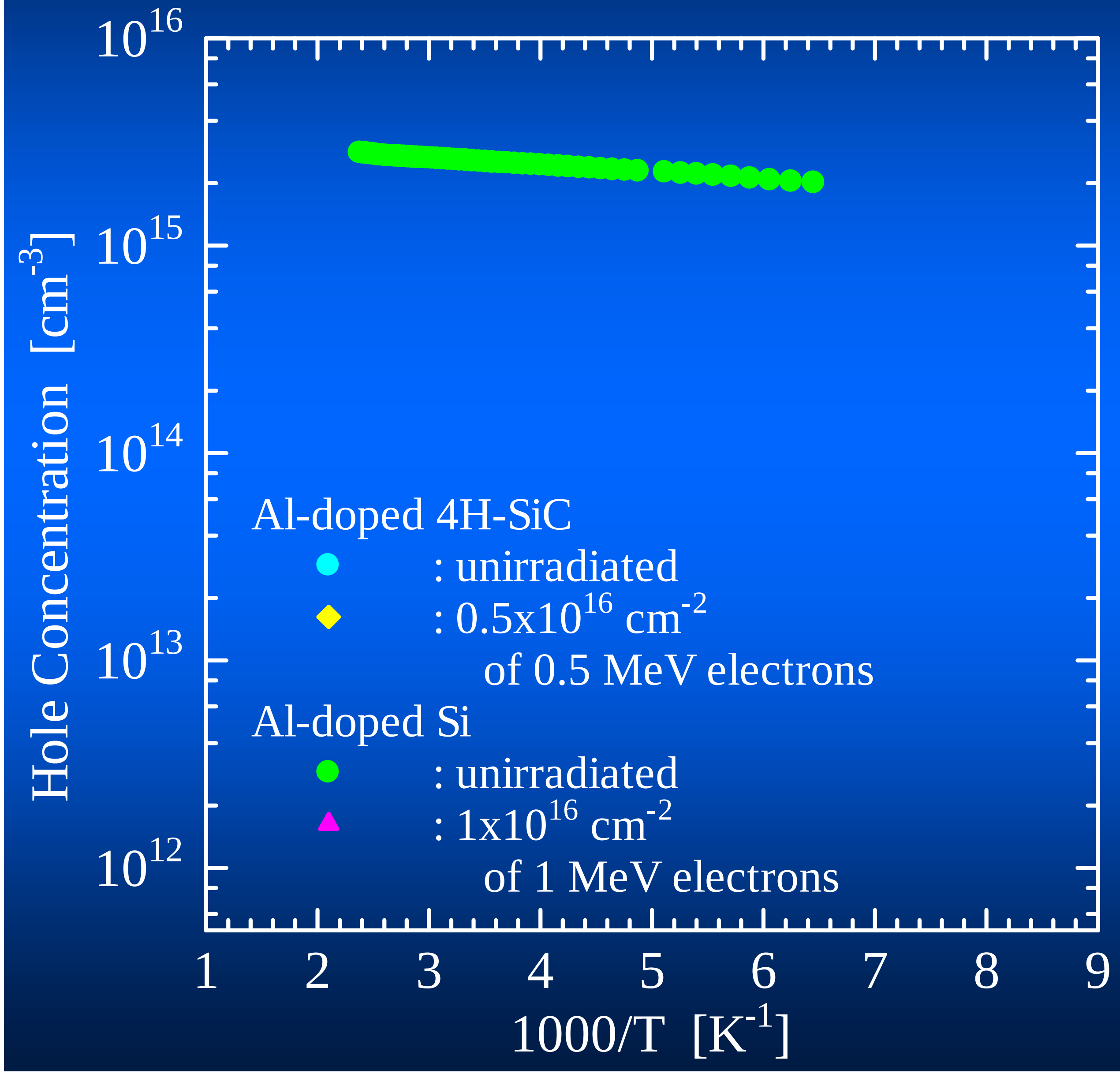
Background of our study

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**.

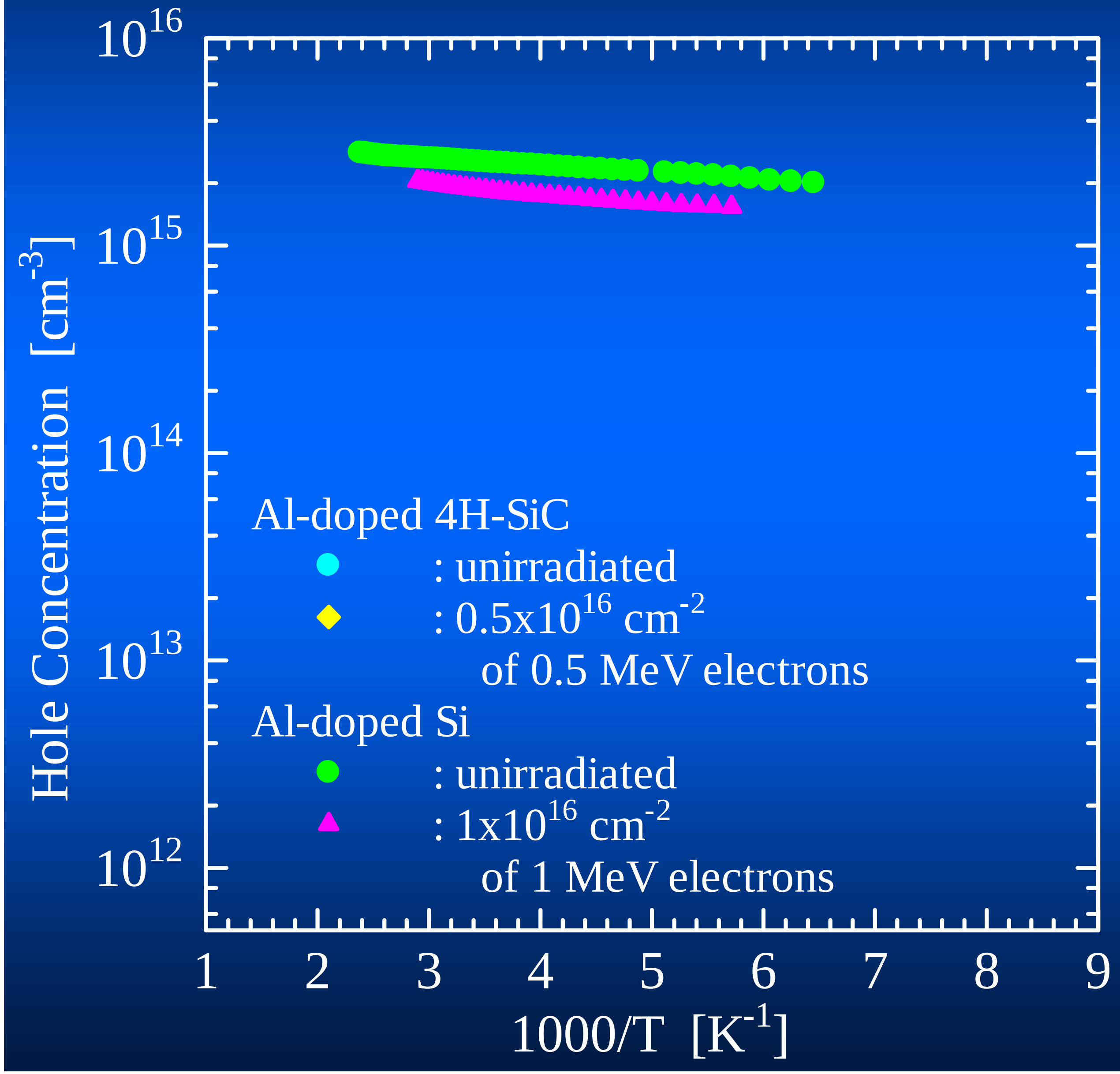
In order to understand the radiation-degradation of SiC electronic devices, changes of properties in SiC by radiation should be investigated.

Comparison of radiation resistance of **Si** and **SiC**



Al-doped Si

Comparison of radiation resistance of Si and SiC



Al-doped Si

Irradiation conditions

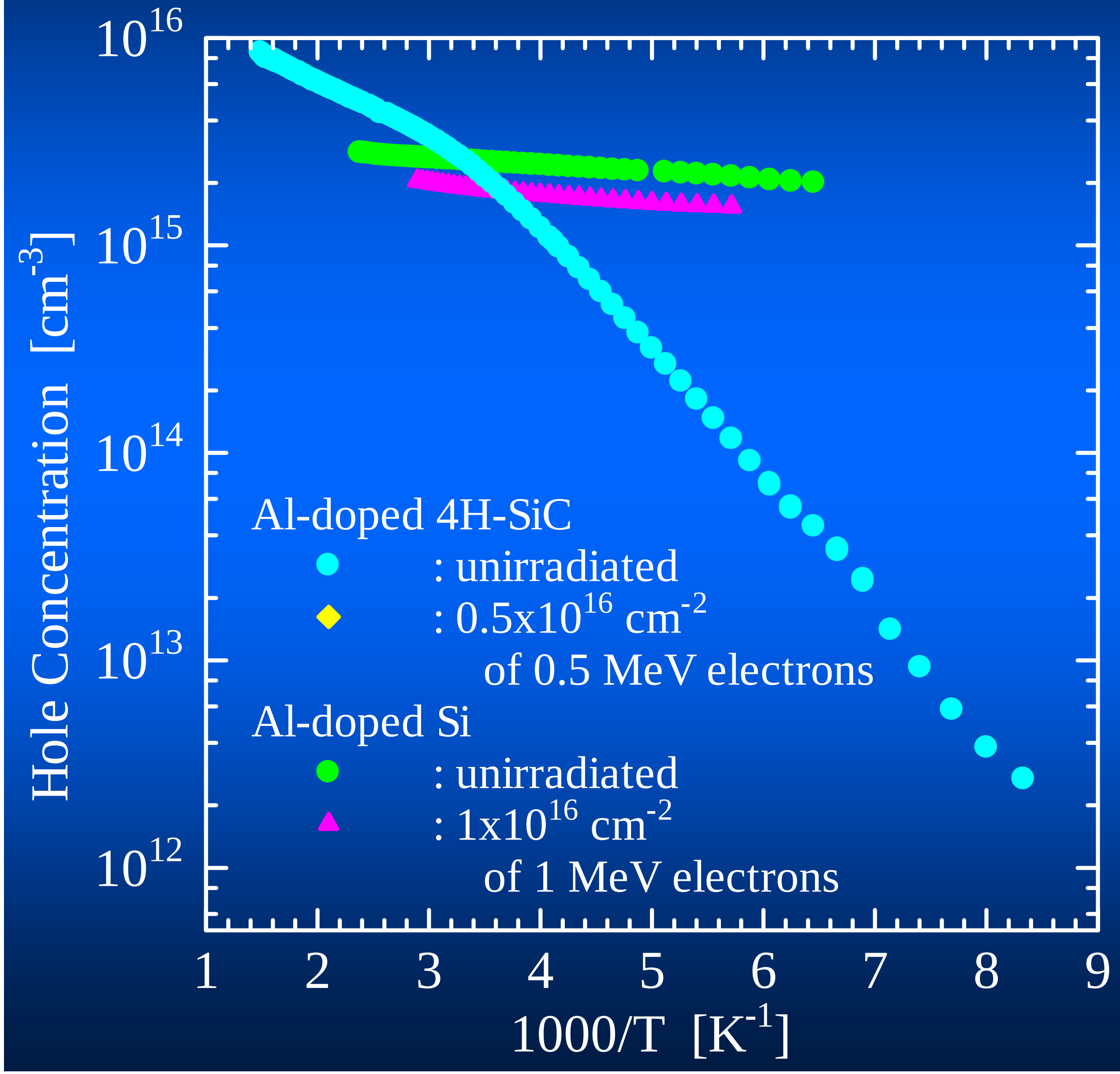
1 MeV electrons

1×10^{16} cm^{-2} fluence

⇩

p(T) decreased slightly.

Comparison of radiation resistance of **Si** and **SiC**



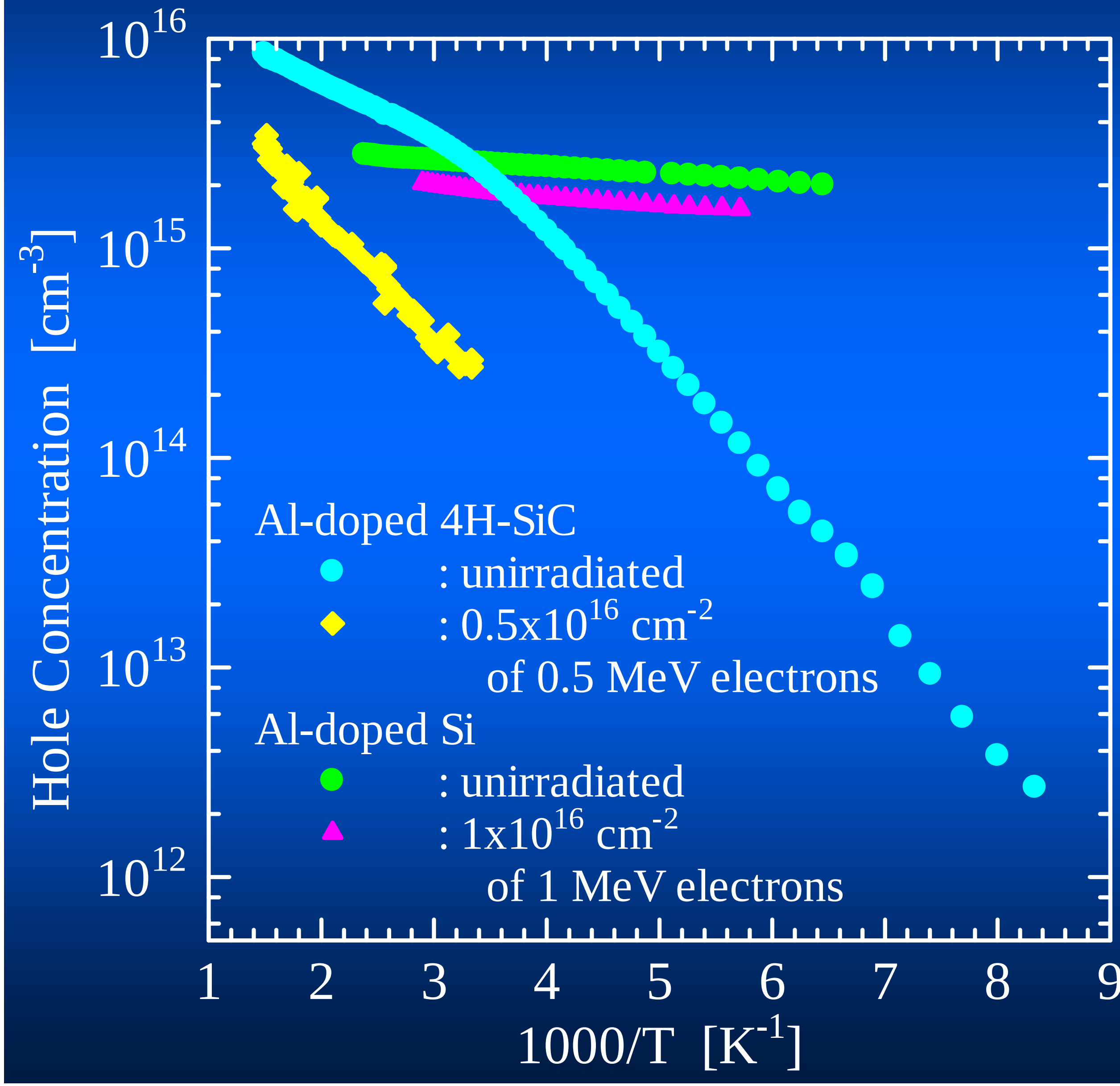
Al-doped Si

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} fluence

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.

To understand the origin of the decrease in p(T) in Al-doped 4H-SiC by electron irradiation, the densities and energy levels of acceptors and defects should be determined from p(T).

How to accurately determine the densities and energy levels of acceptors and defects from p(T)

Free Carrier Concentration Spectroscopy (FCCS)

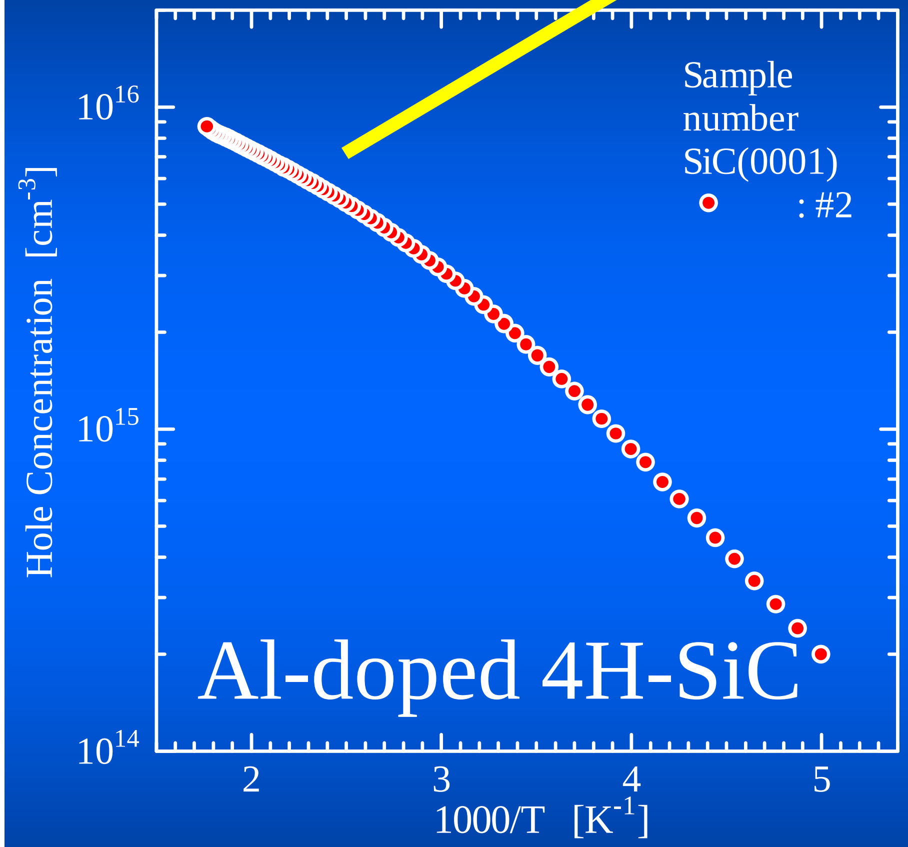
$$H(T,E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right)$$

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

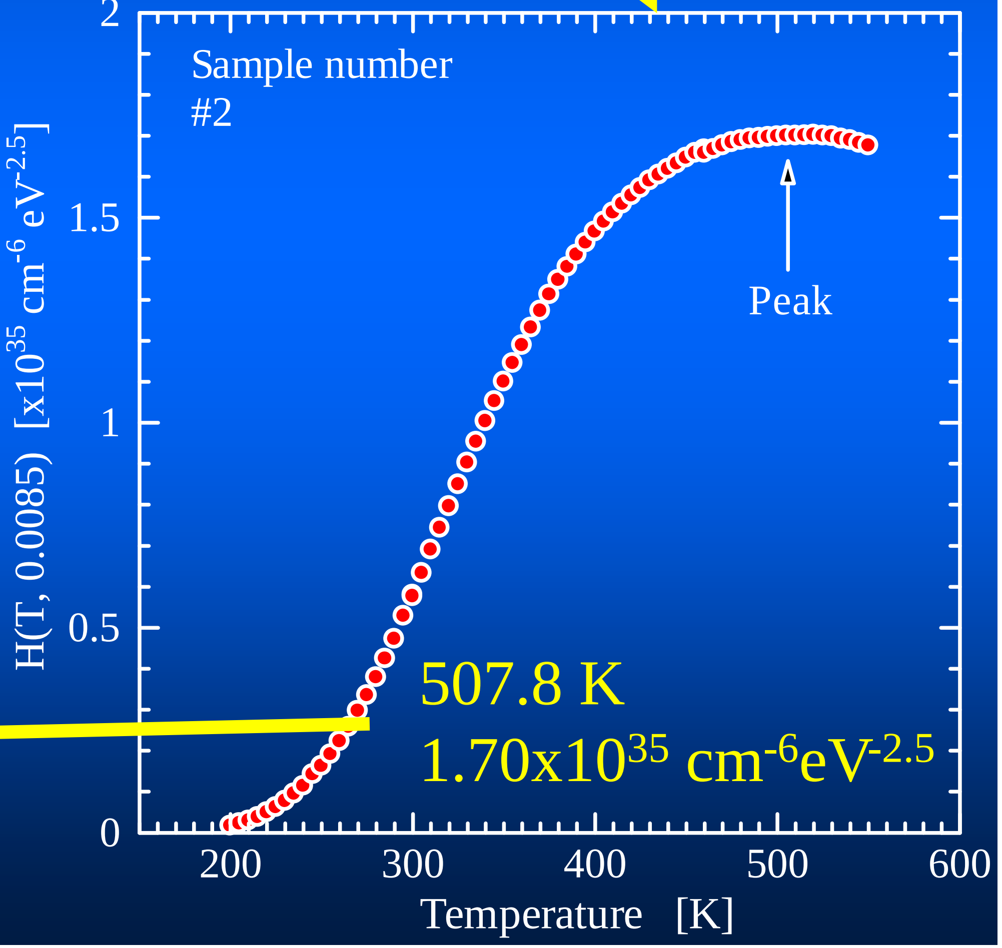
$$\Delta E_i \cong kT_{\mathrm{peak}i} + E_{\mathrm{ref}}$$

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

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



Al-doped 4H-SiC



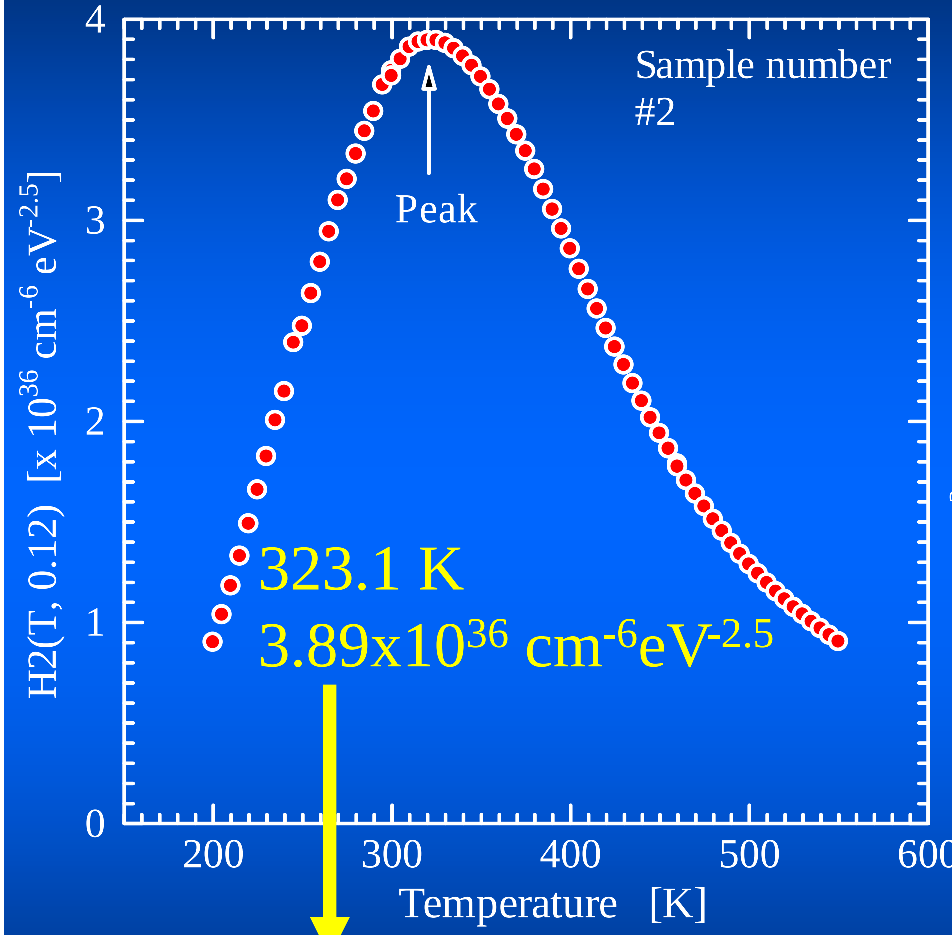
507.8 K

1.70×10^{35} cm^{-6}eV$^{-2.5}$

348.7 meV

4.15×10^{15} cm^{-3}

FCCS signal of H2(T, E_{ref}), in which the influence of the previously determined acceptor is removed, is calculated



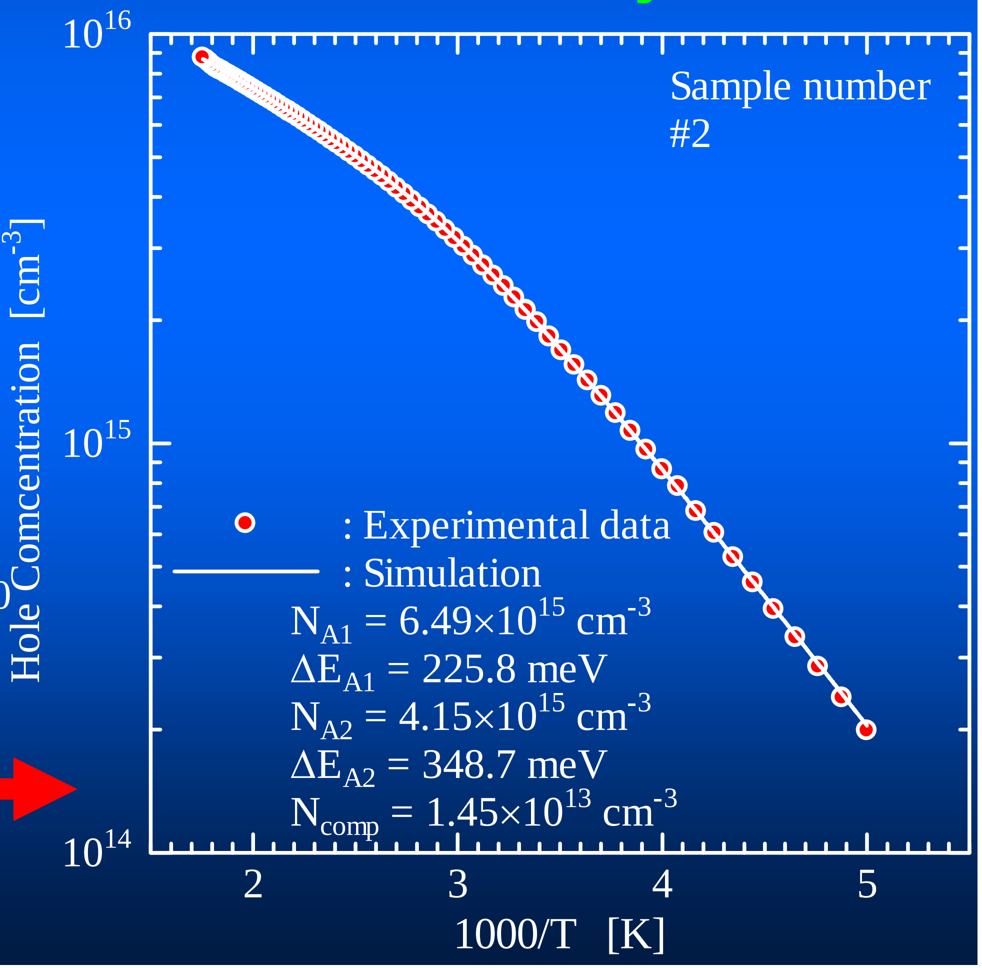
323.1 K

3.89×10^{36} $cm^{-6} eV^{-2.5}$

225.8 meV

6.49×10^{15} cm^{-3}

To verify the results determined by FCCS



$N_{A1} = 6.49 \times 10^{15}$ cm^{-3}

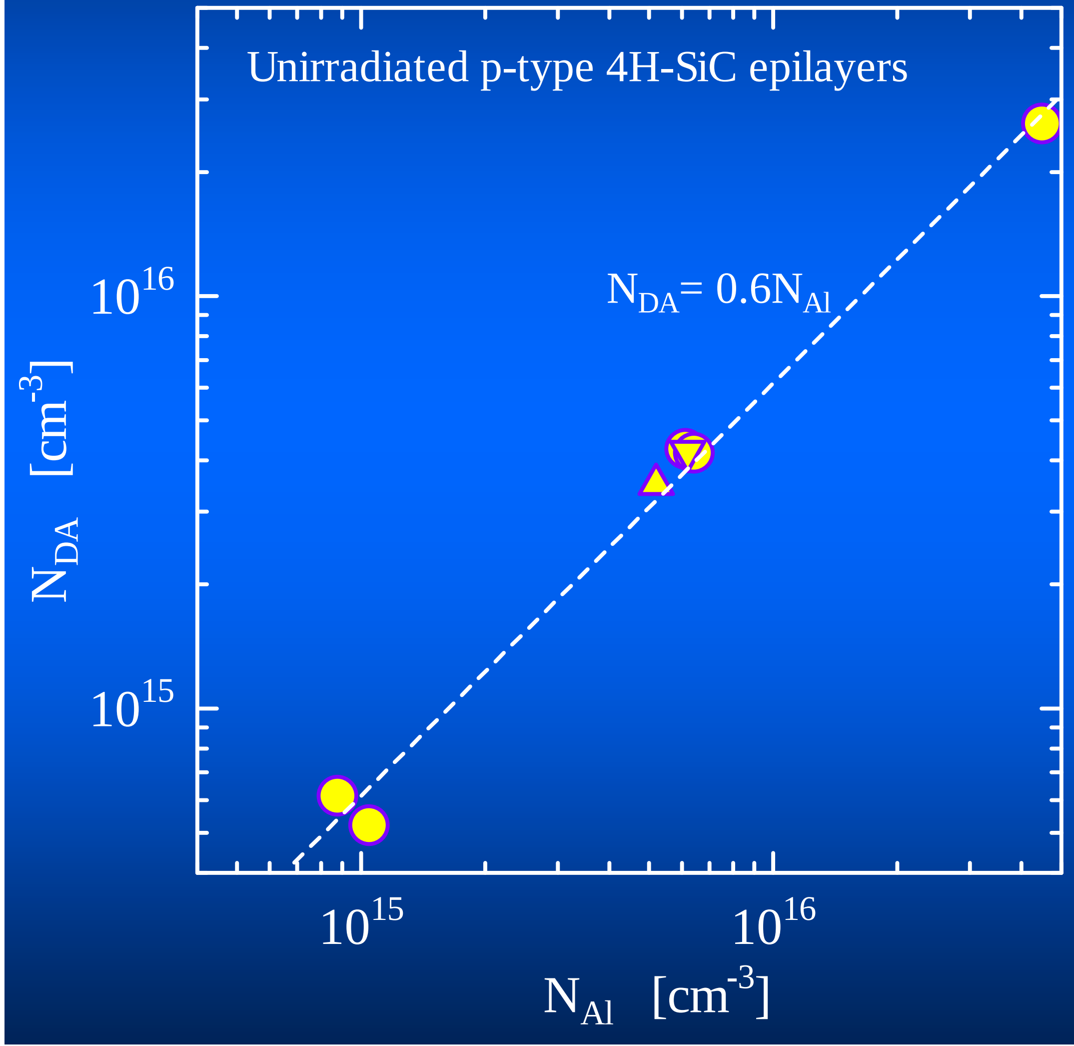
$\Delta E_{A1} = 225.8$ meV

$N_{A2} = 4.15 \times 10^{15}$ cm^{-3}

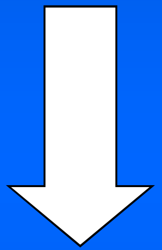
$\Delta E_{A2} = 348.7$ meV

$N_{comp} = 1.45 \times 10^{13}$ cm^{-3}

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

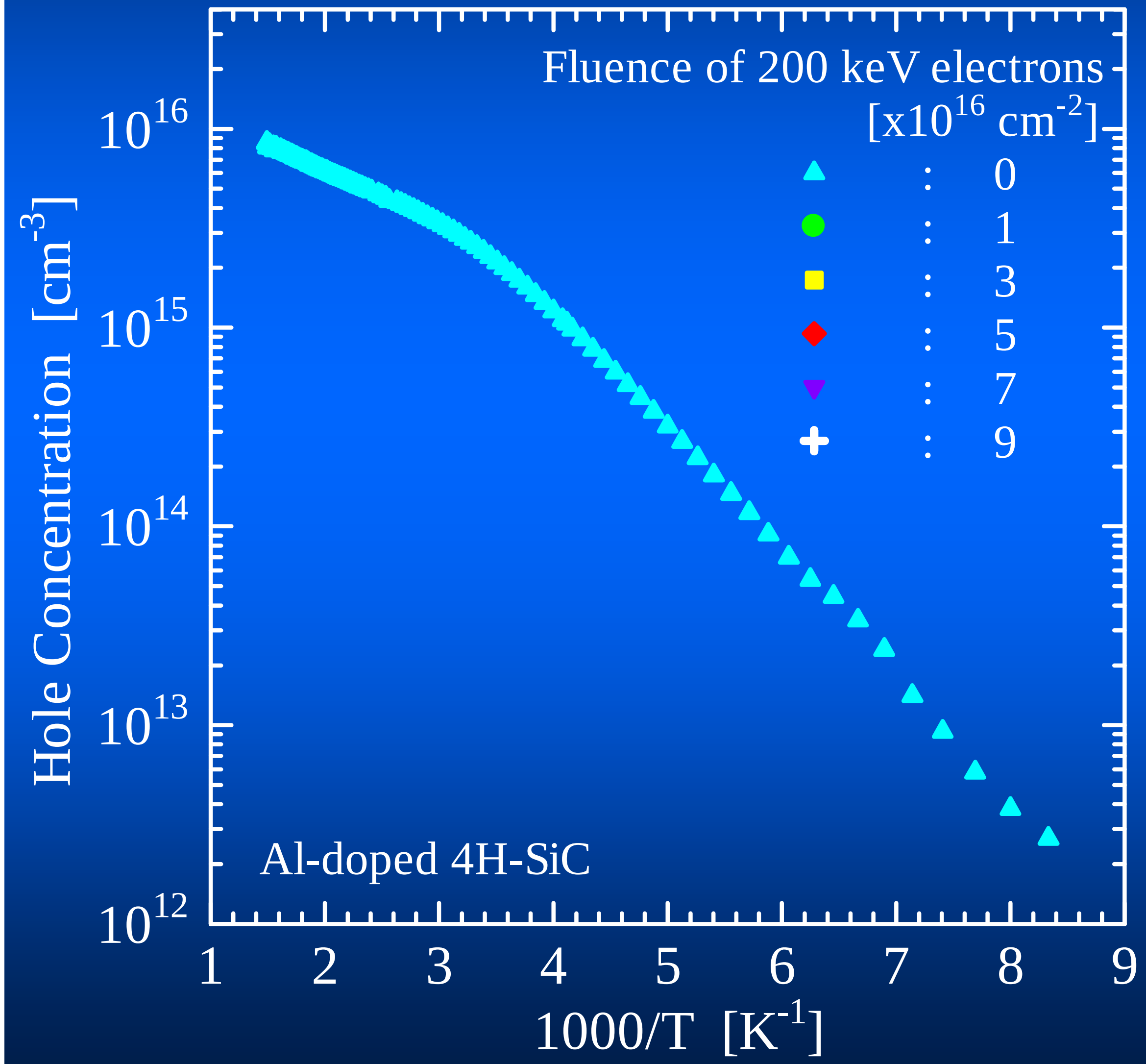


$$N_{DA} = 0.6 \times N_{Al}$$



The unknown deep acceptor is most likely related to Al

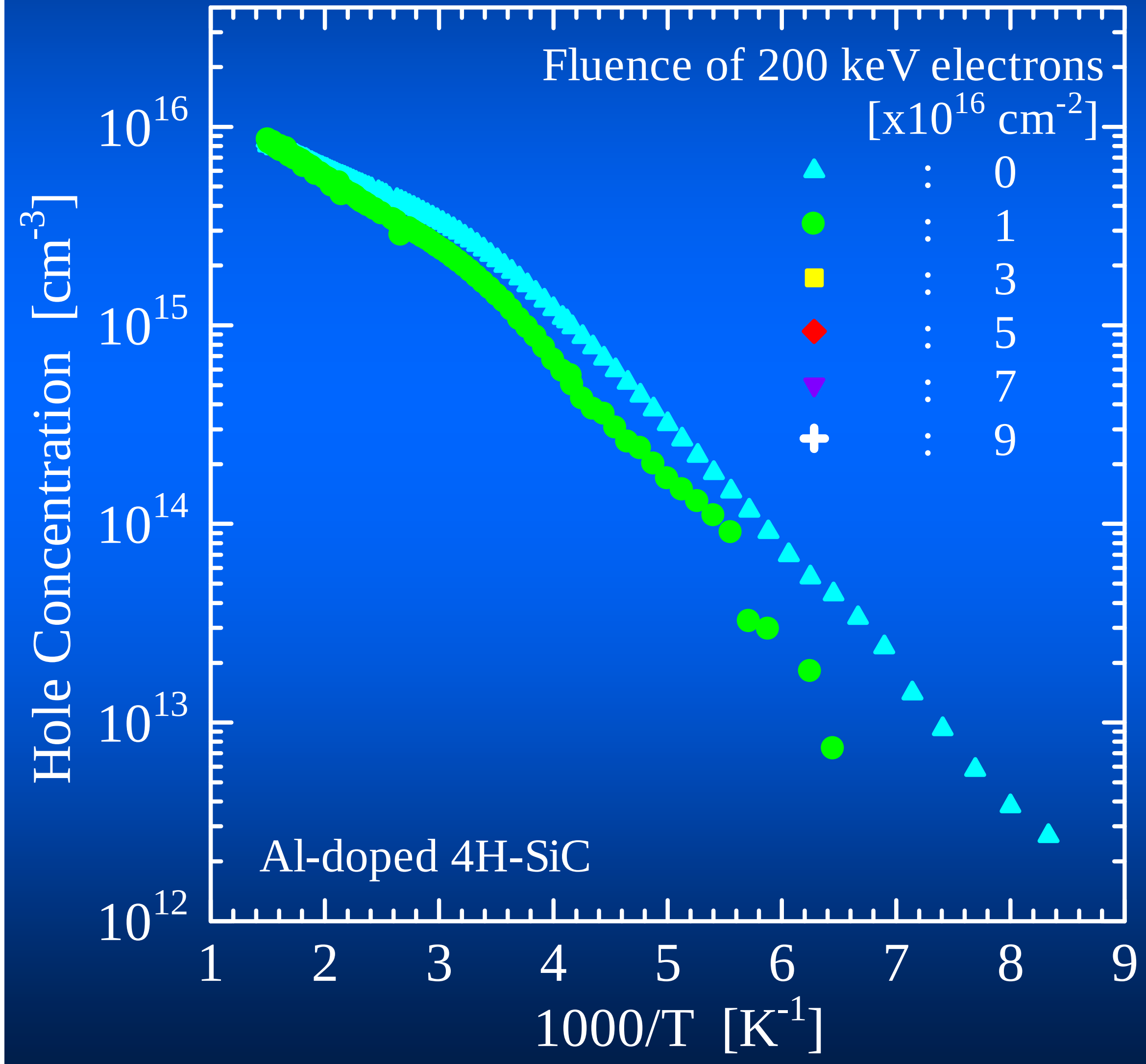
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

0

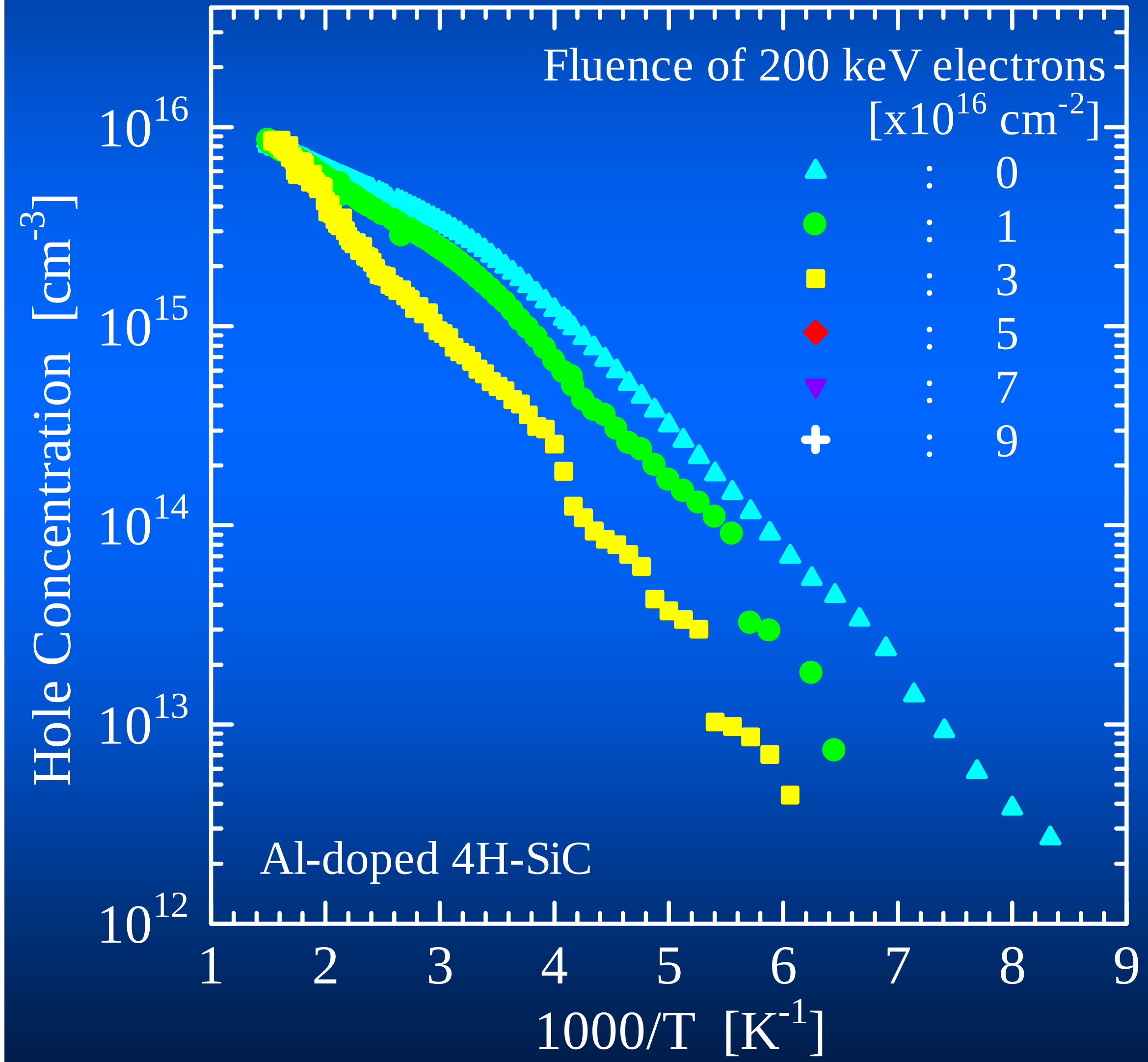
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

1×10^{16}

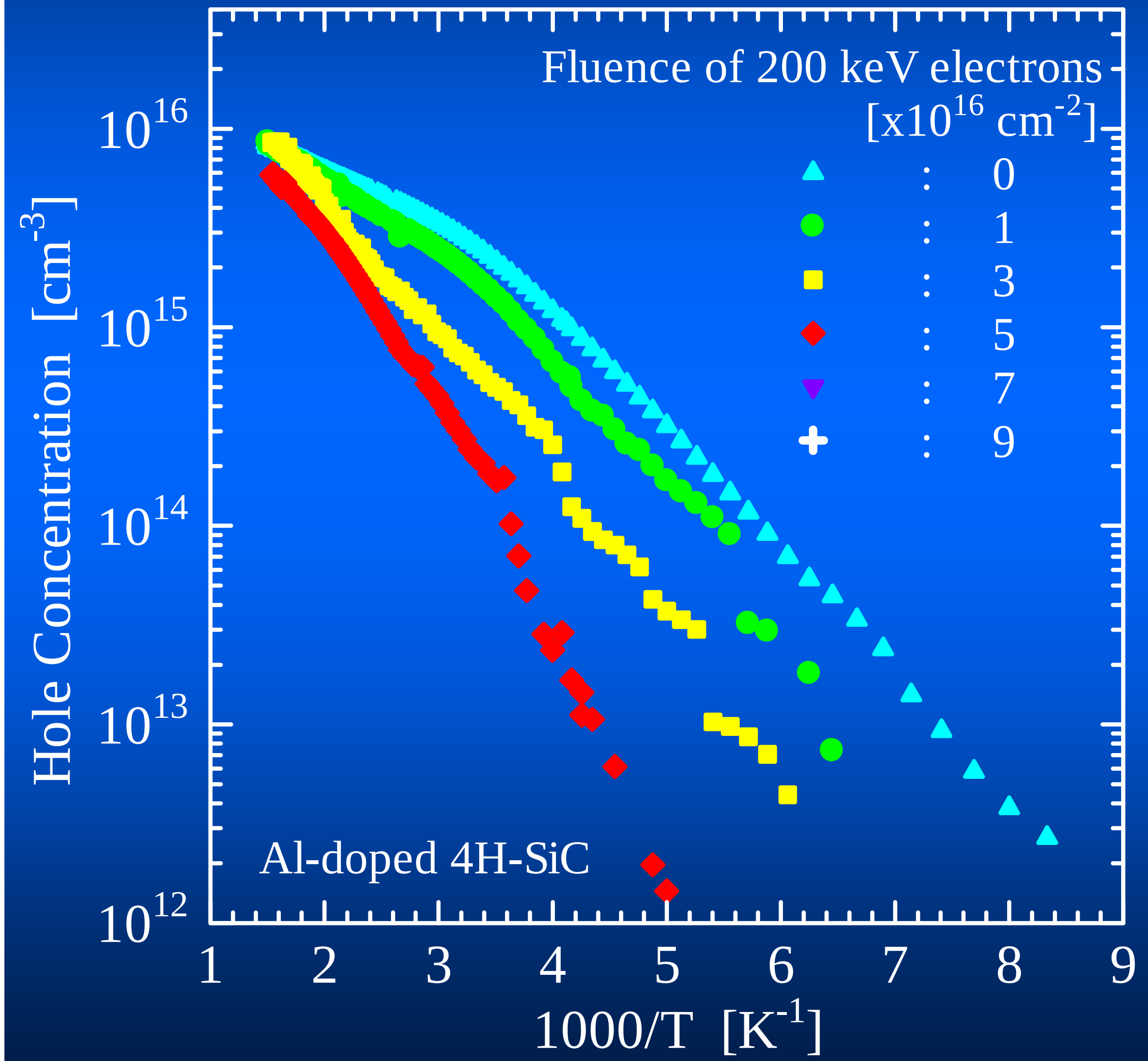
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

3×10^{16}

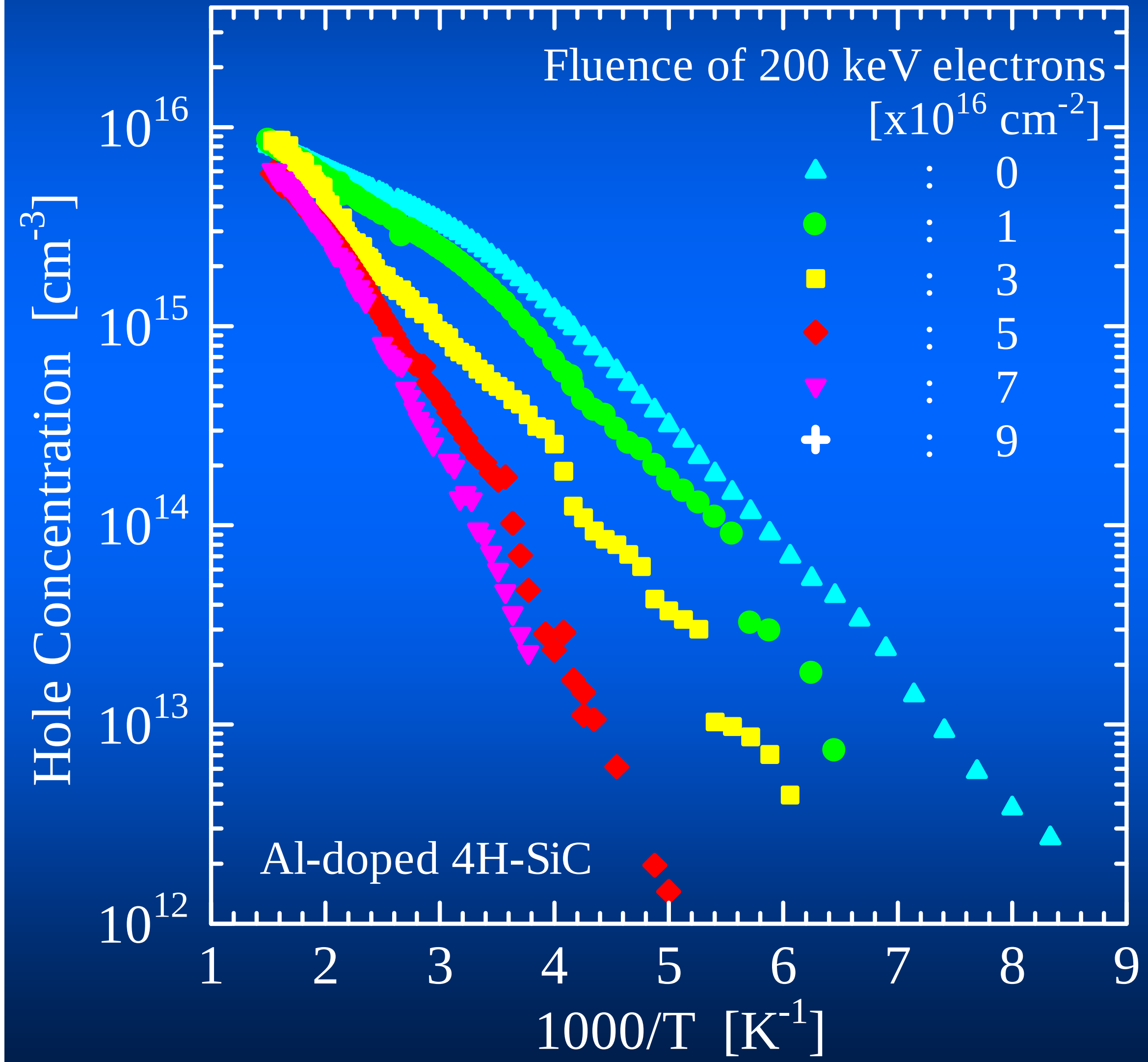
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

5×10^{16}

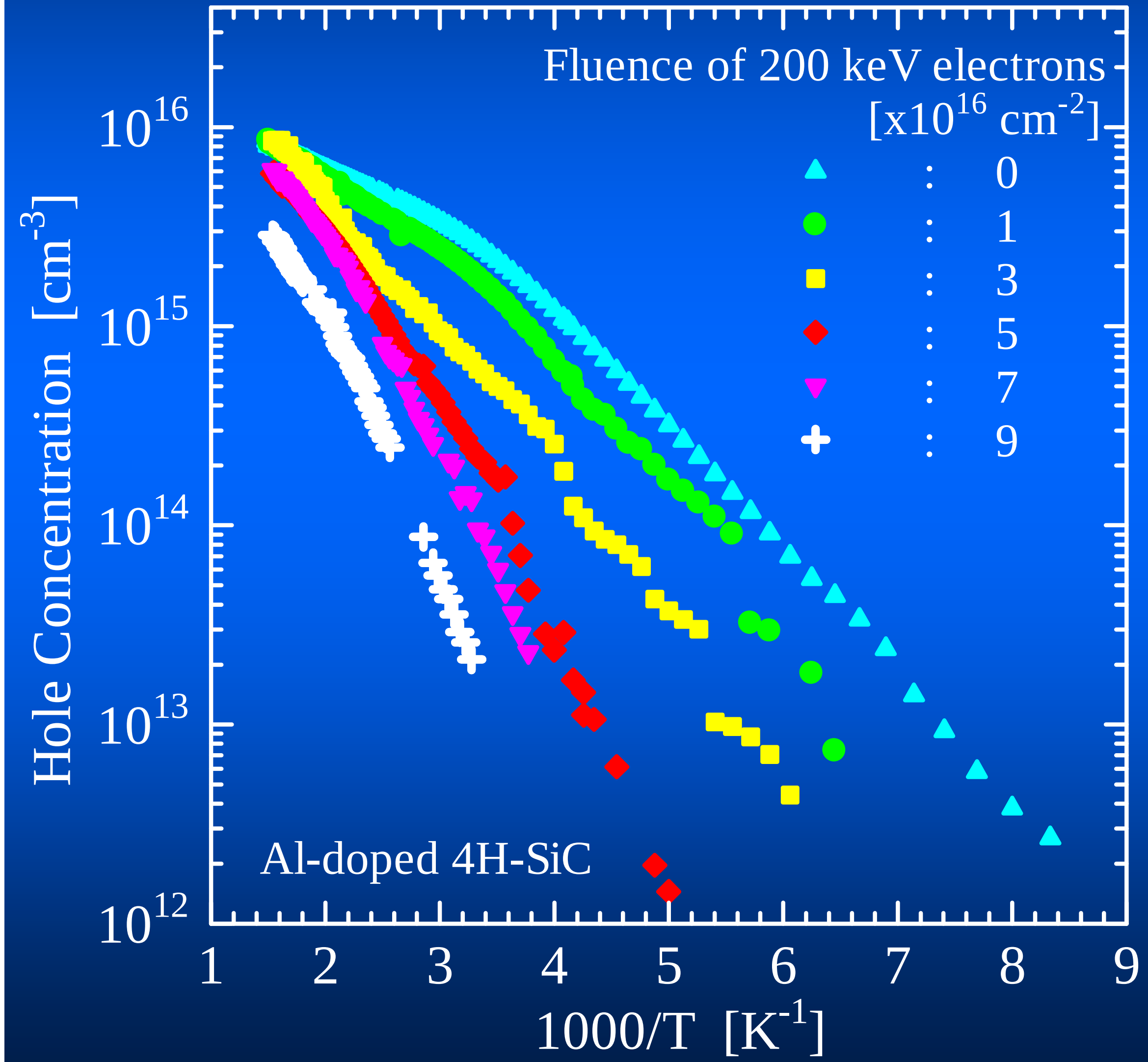
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

7×10^{16}

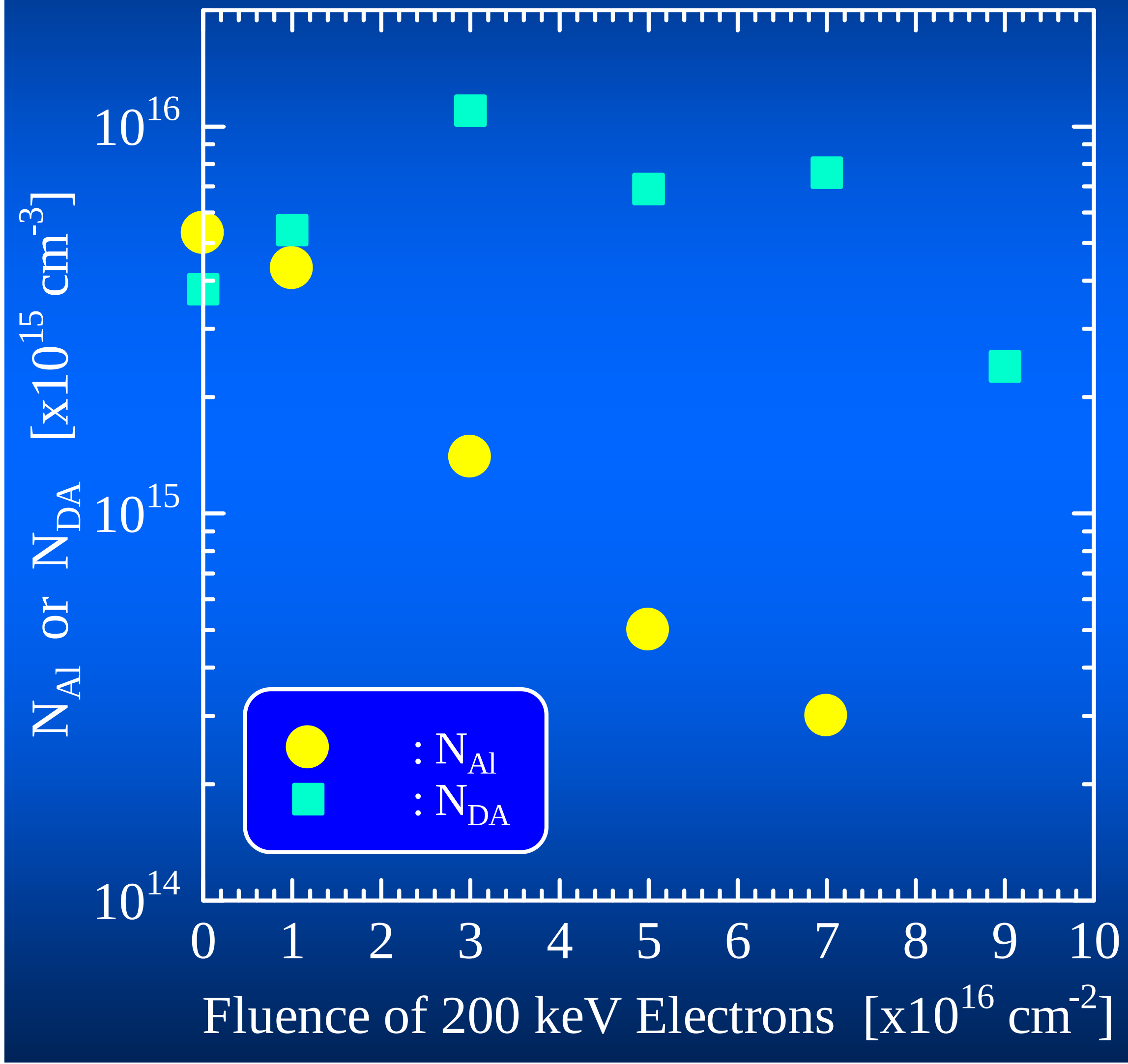
Reduction in p(T) in Al-doped p-type 4H-SiC by **200 keV** electron irradiation



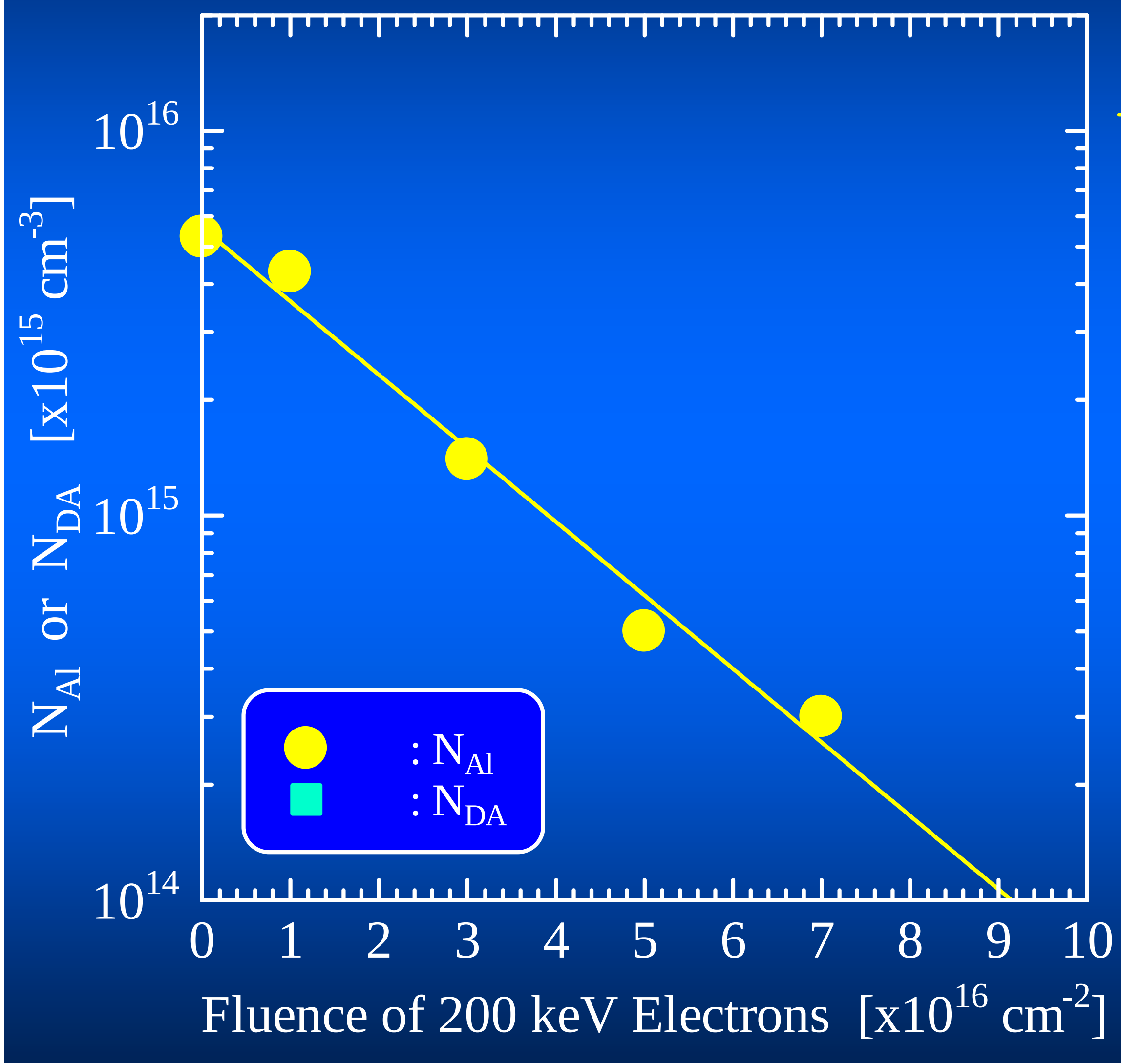
Fluence [cm^{-2}]

9×10^{16}

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



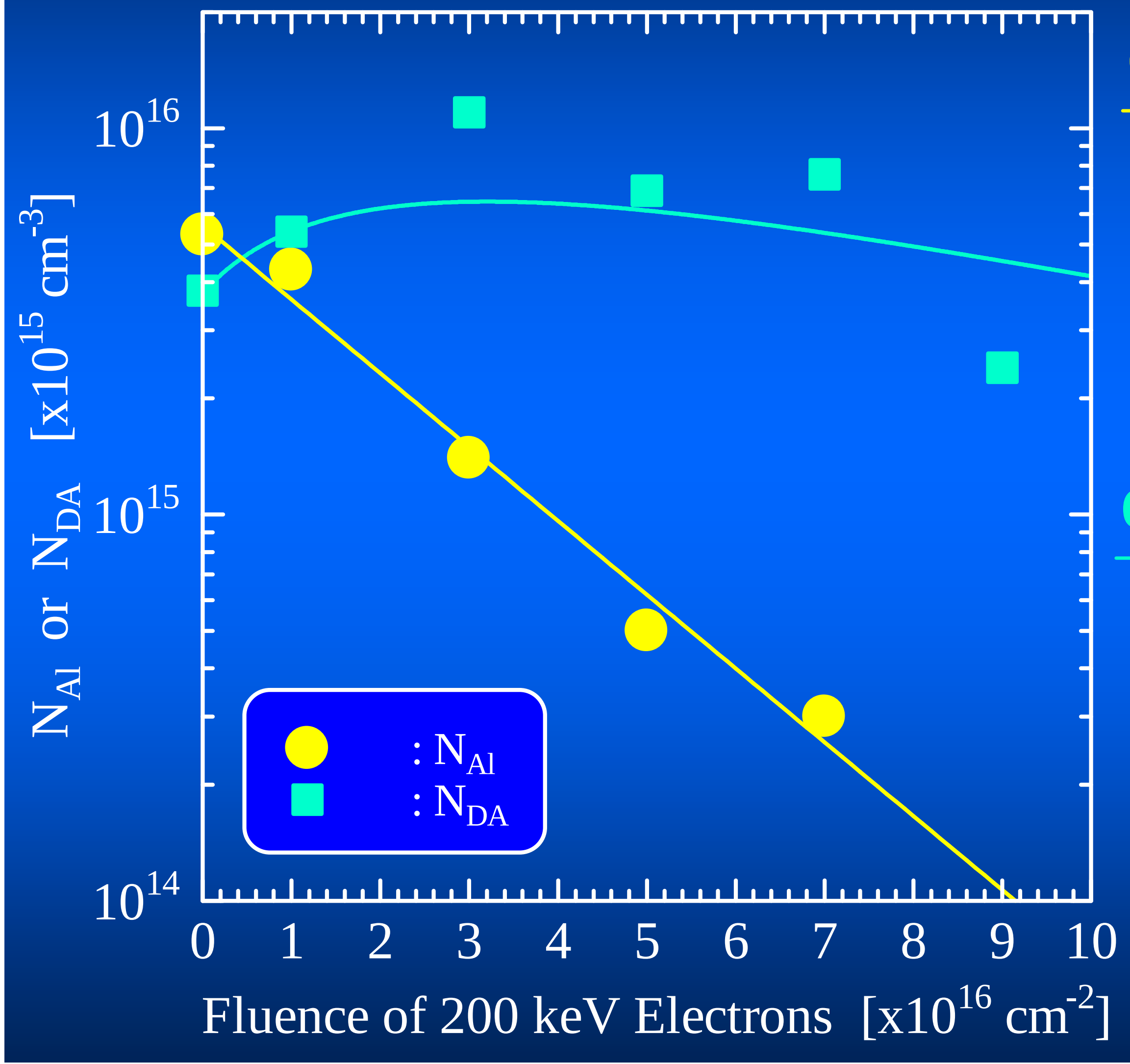
Fluence Dependence of N_{Al} in 4H-SiC



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

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

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



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

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

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

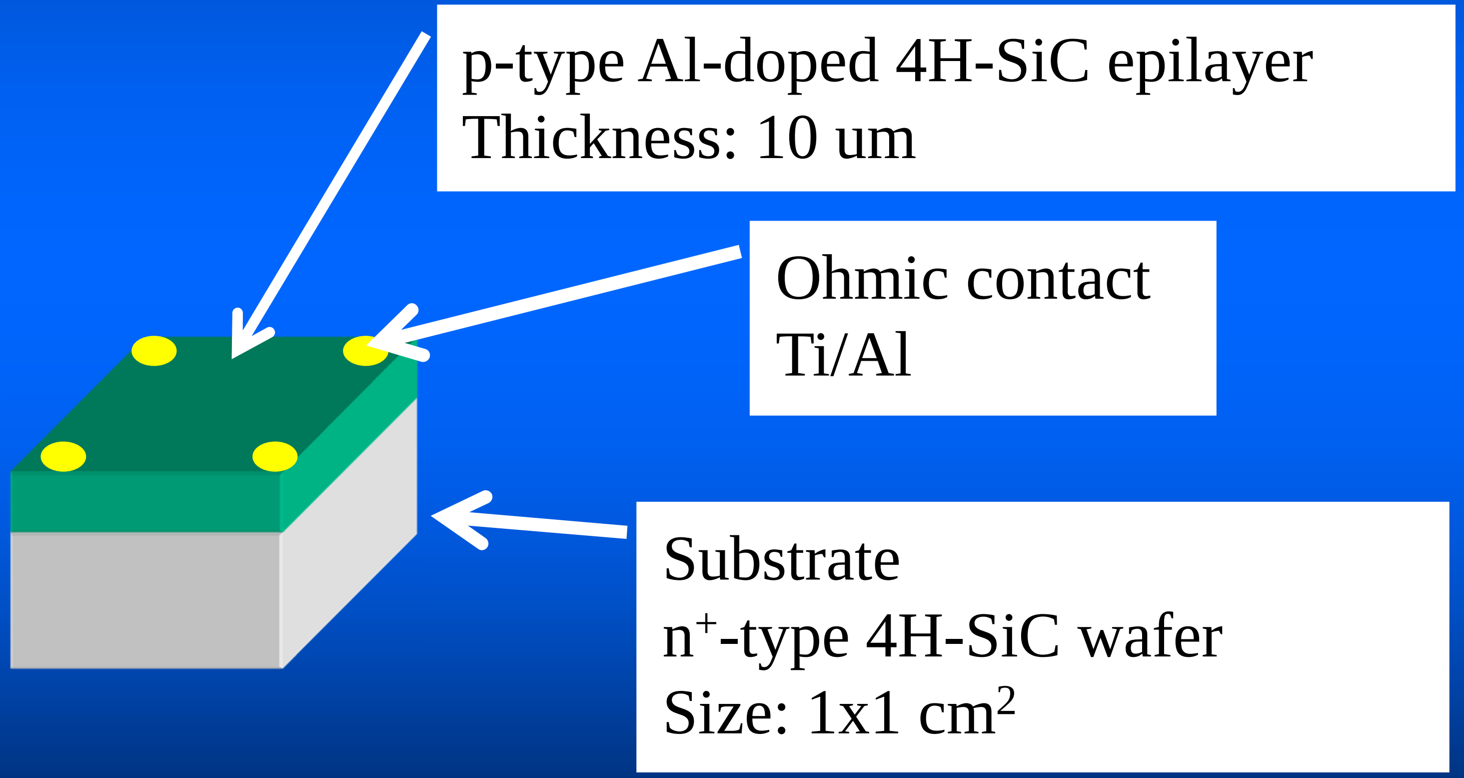
$$\kappa_{DA} = 1.0 \times 10^{-17} \text{ cm}^2$$

Motivation of our study

1. To investigate changes of p(T) in Al-doped 4H-SiC by electron irradiation with lower energies (100 or 150 keV)
2. To investigate decreases of n(T) in N-doped 4H-SiC by 200 keV electron irradiation

Sample Configuration

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

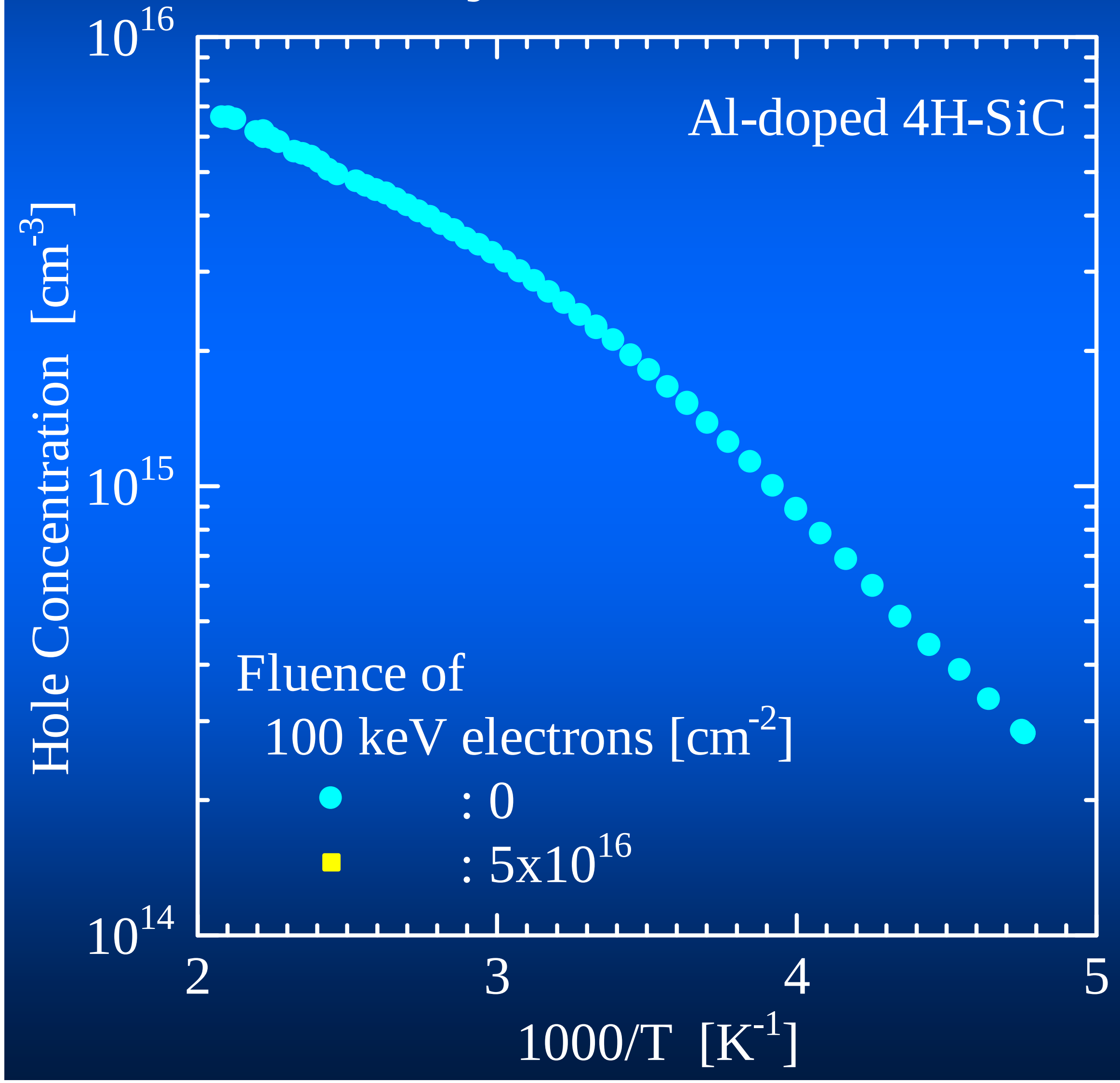


p-type Al-doped 4H-SiC epilayer
Thickness: 10 um

Ohmic contact
Ti/Al

Substrate
n^+-type 4H-SiC wafer
Size: 1x1 cm^2

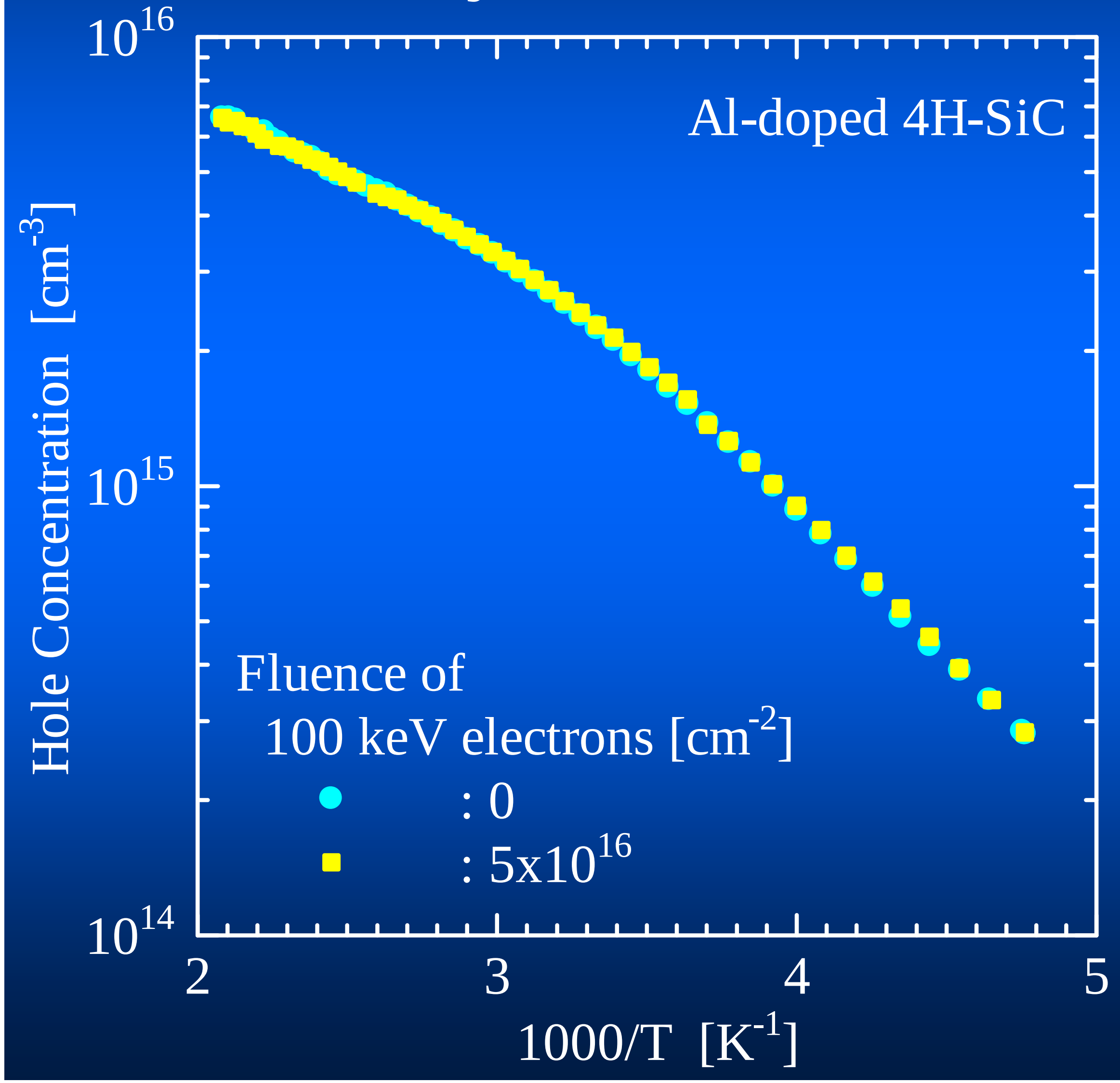
Change in p(T) in Al-doped p-type 4H-SiC by **100 keV** electron irradiation



Fluence [cm^{-2}]

0

Change in p(T) in Al-doped p-type 4H-SiC by **100 keV** electron irradiation

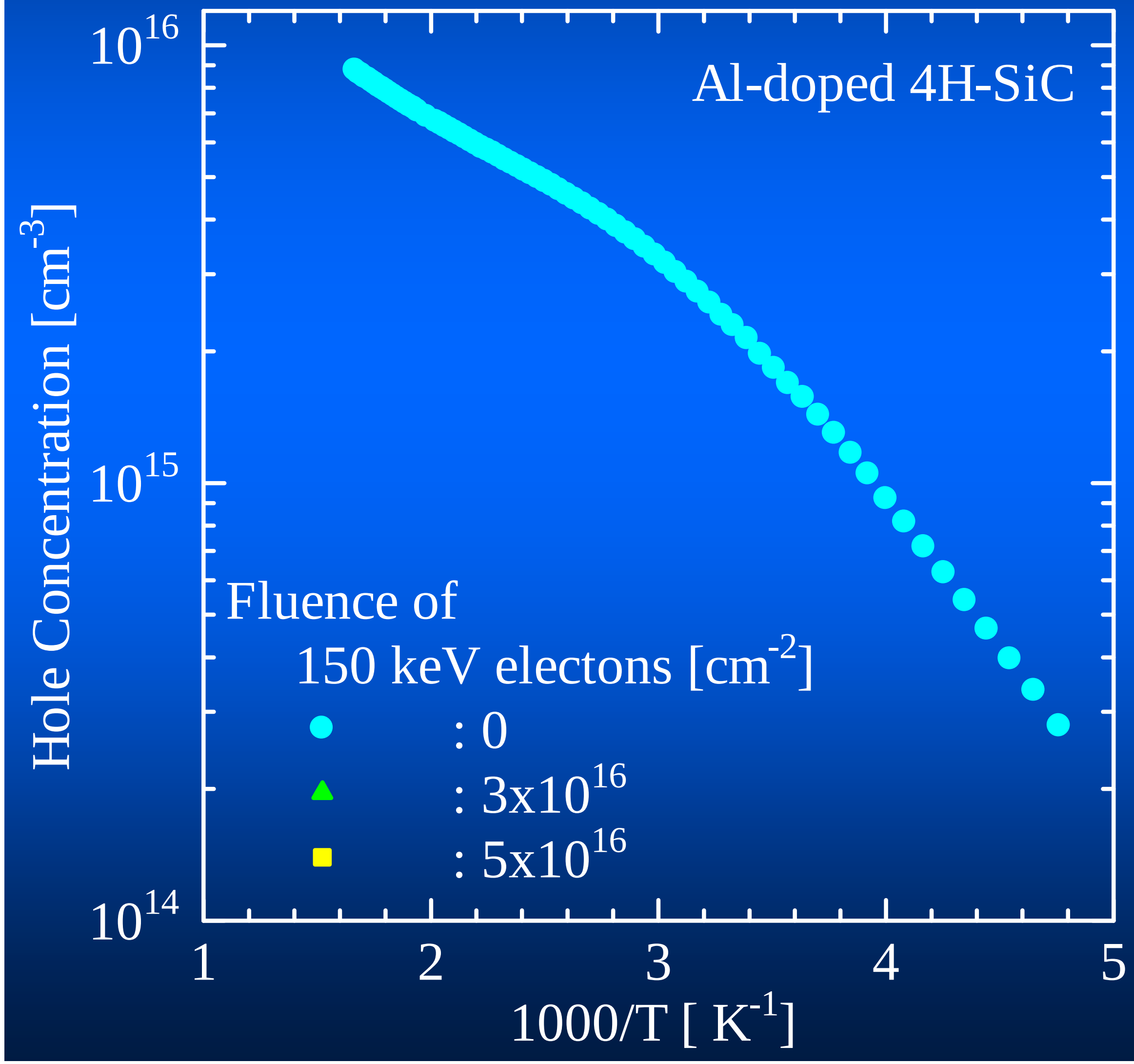


Fluence [cm^{-2}]

5×10^{16}

100 keV electron irradiation could not reduce p(T).

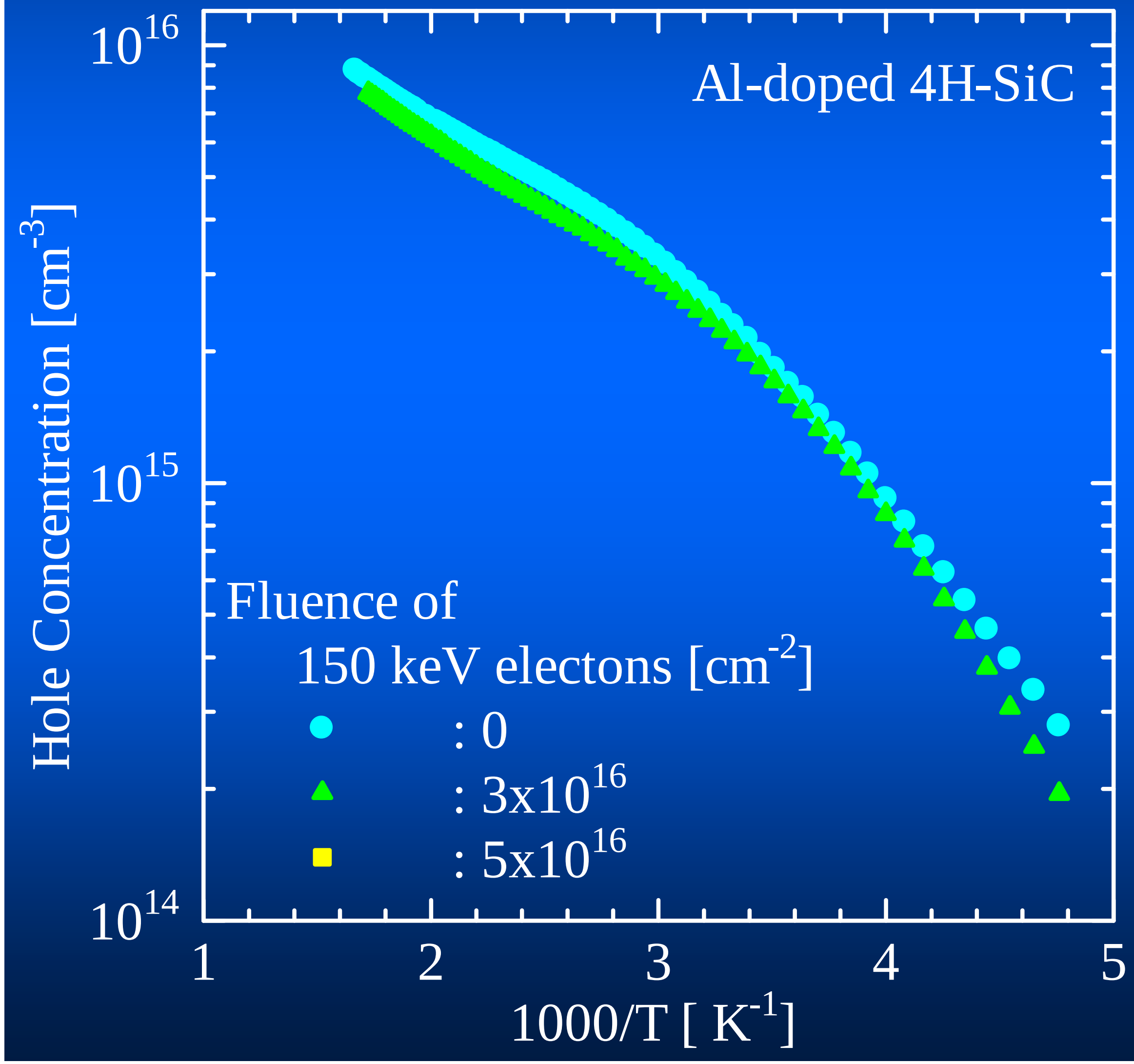
Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

0

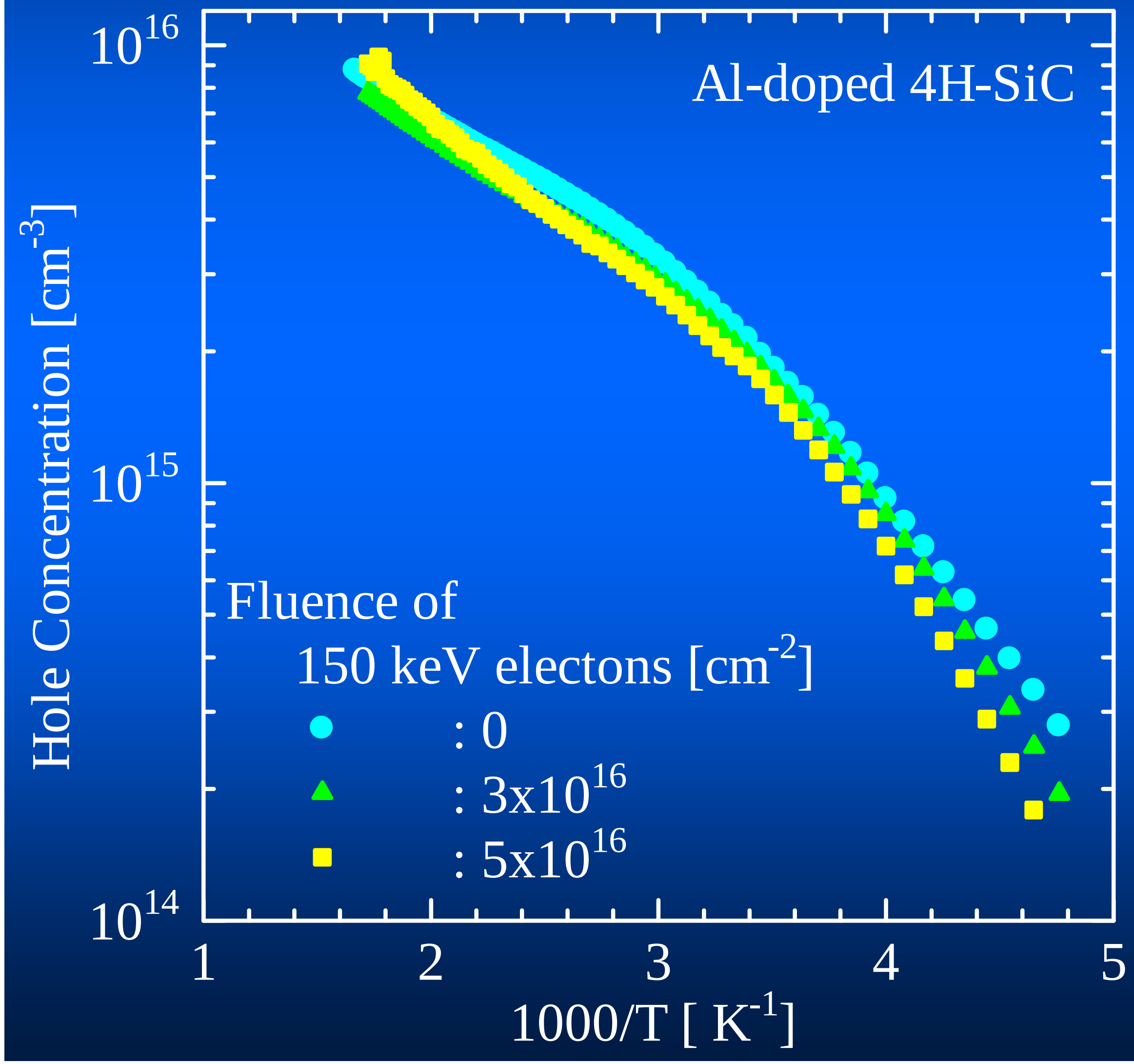
Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

3×10^{16}

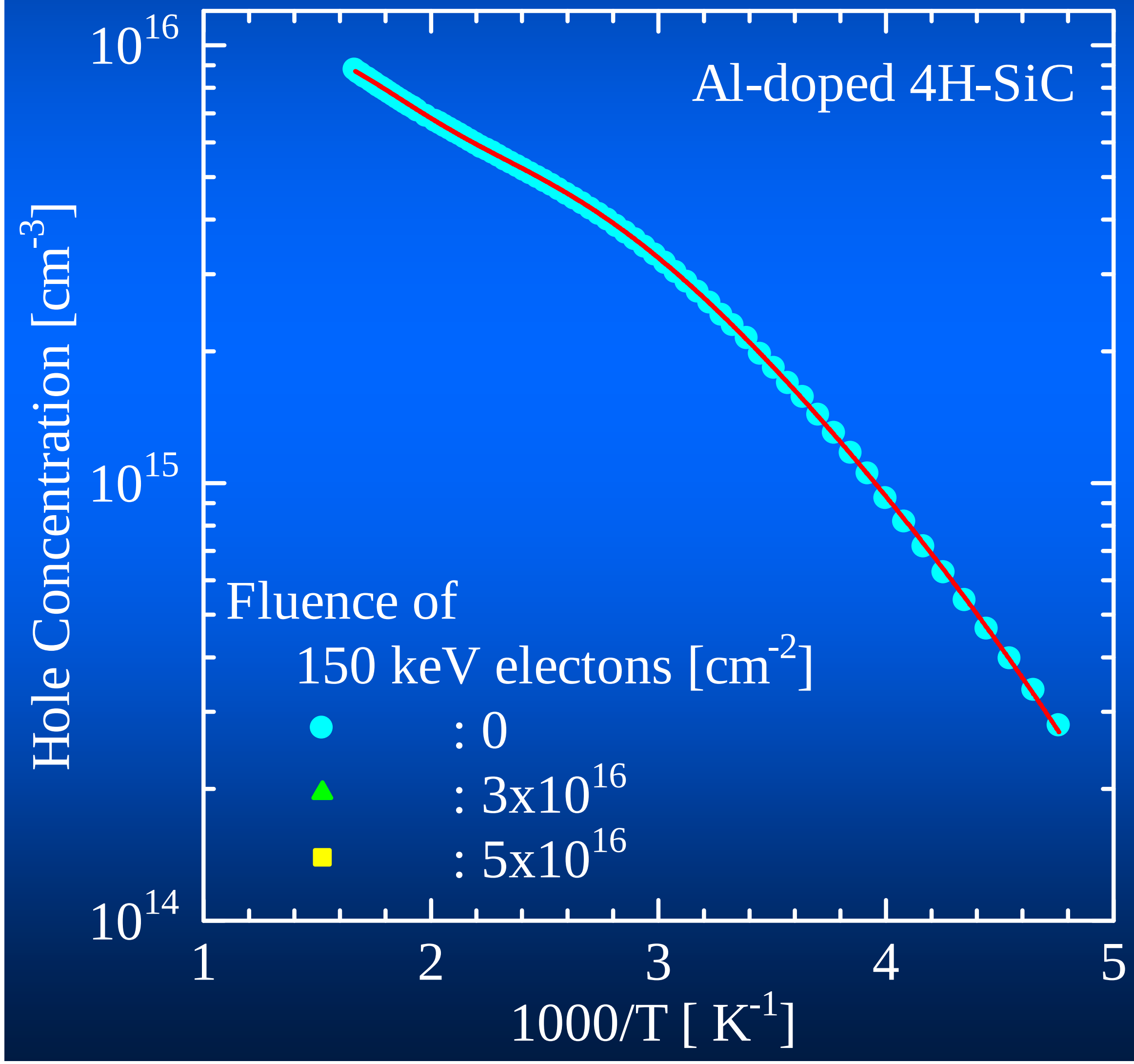
Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

5×10^{16}

Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

0

Simulation Result

$N_{Al} = 6.3 \times 10^{15} cm^{-3}$

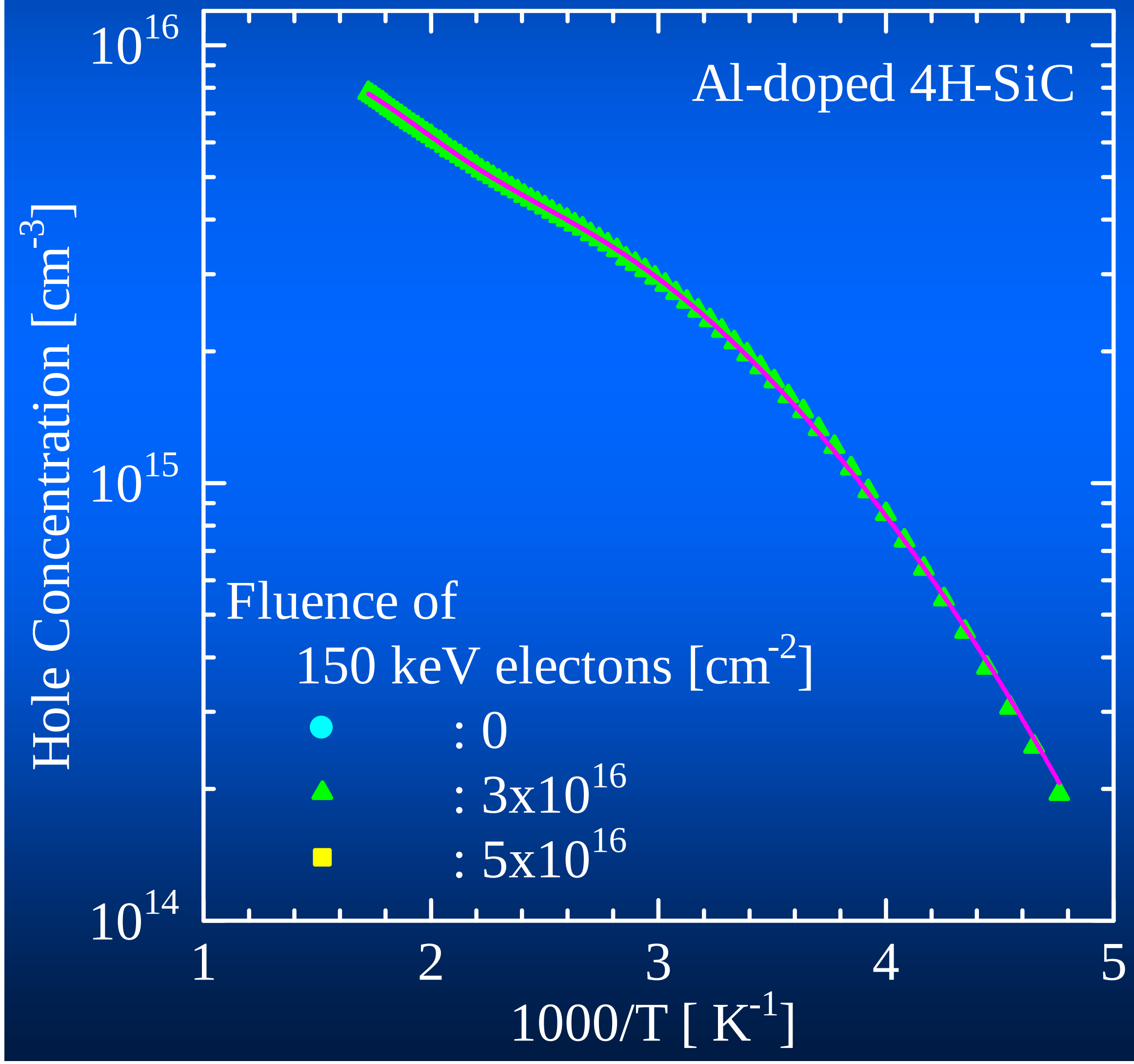
$E_{Al} = E_V + 0.22$ eV

$N_{DA} = 4.9 \times 10^{15} cm^{-3}$

$E_{DA} = E_V + 0.38$ eV

$N_{comp} = 2.7 \times 10^{14} cm^{-3}$

Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

3×10^{16}

Simulation Result

$N_{\mathrm{Al}} = 5.5\times10^{15}\mathrm{cm}^{-3}$

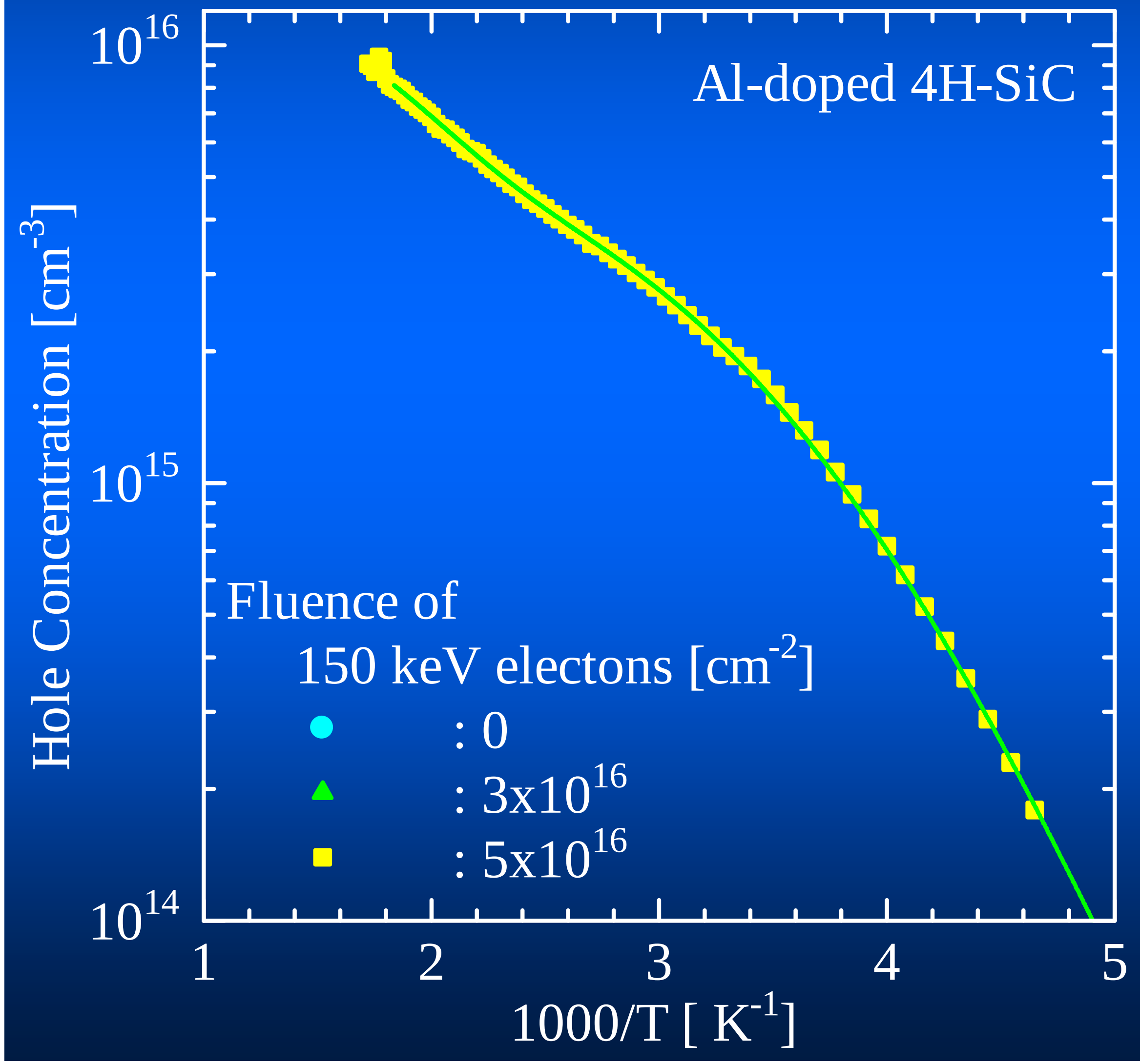
$E_{\mathrm{Al}} = E_{\mathrm{V}} + 0.21\mathrm{eV}$

$N_{\mathrm{DA}} = 5.1\times10^{15}\mathrm{cm}^{-3}$

$E_{\mathrm{DA}} = E_{\mathrm{V}} + 0.36\ \mathrm{eV}$

$N_{\mathrm{comp}} = 6.9\times10^{14}\mathrm{cm}^{-3}$

Reduction in p(T) in Al-doped p-type 4H-SiC by **150 keV** electron irradiation



Fluence [cm^{-2}]

5×10^{16}

Simulation Result

$$N_{\mathrm{Al}} = 6.0\times10^{15}\mathrm{cm}^{-3}$$

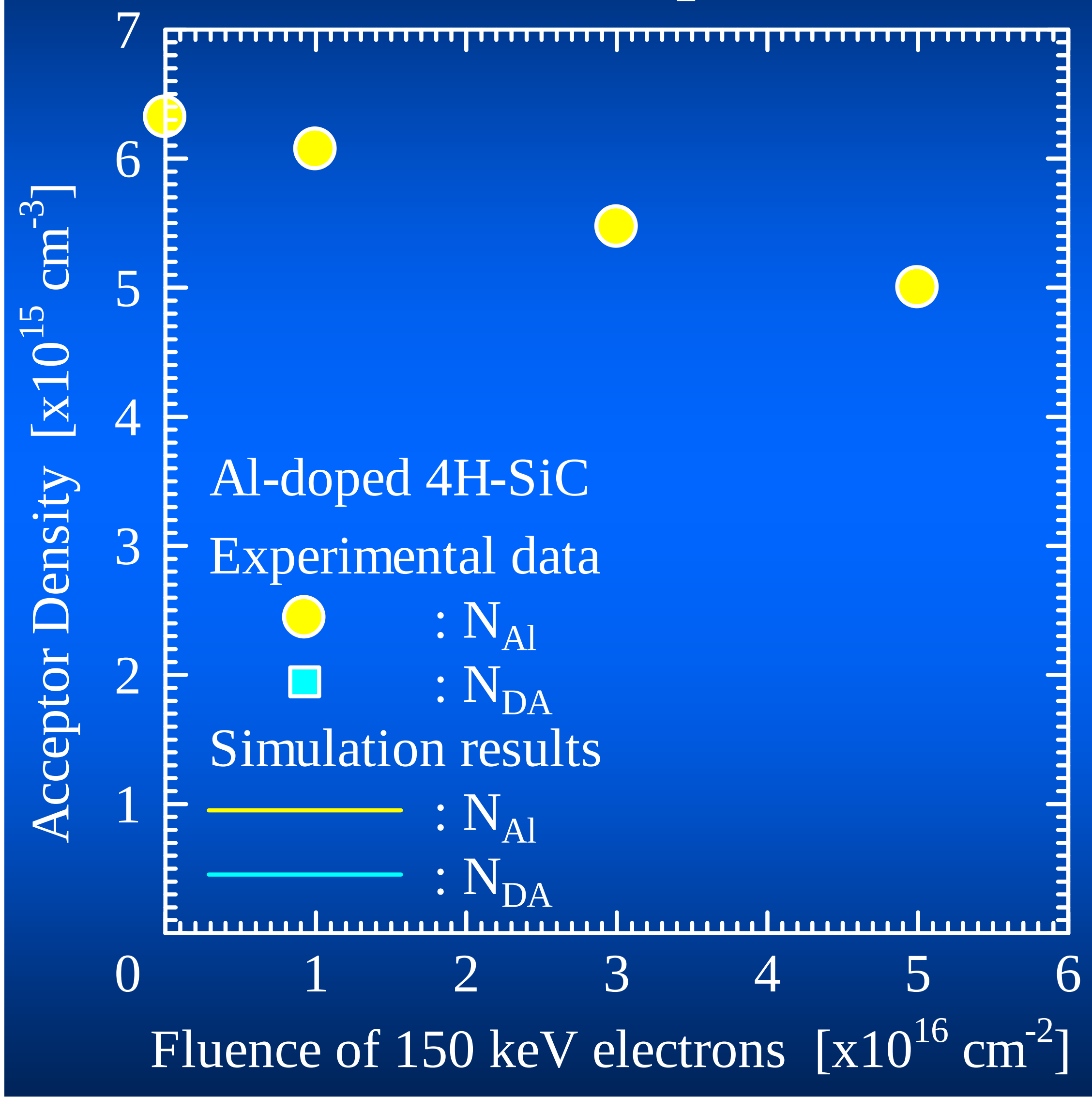
$$E_{\mathrm{Al}} = E_{\mathrm{V}} + 0.20\ \mathrm{eV}$$

$$N_{\mathrm{DA}} = 7.4\times10^{15}\mathrm{cm}^{-3}$$

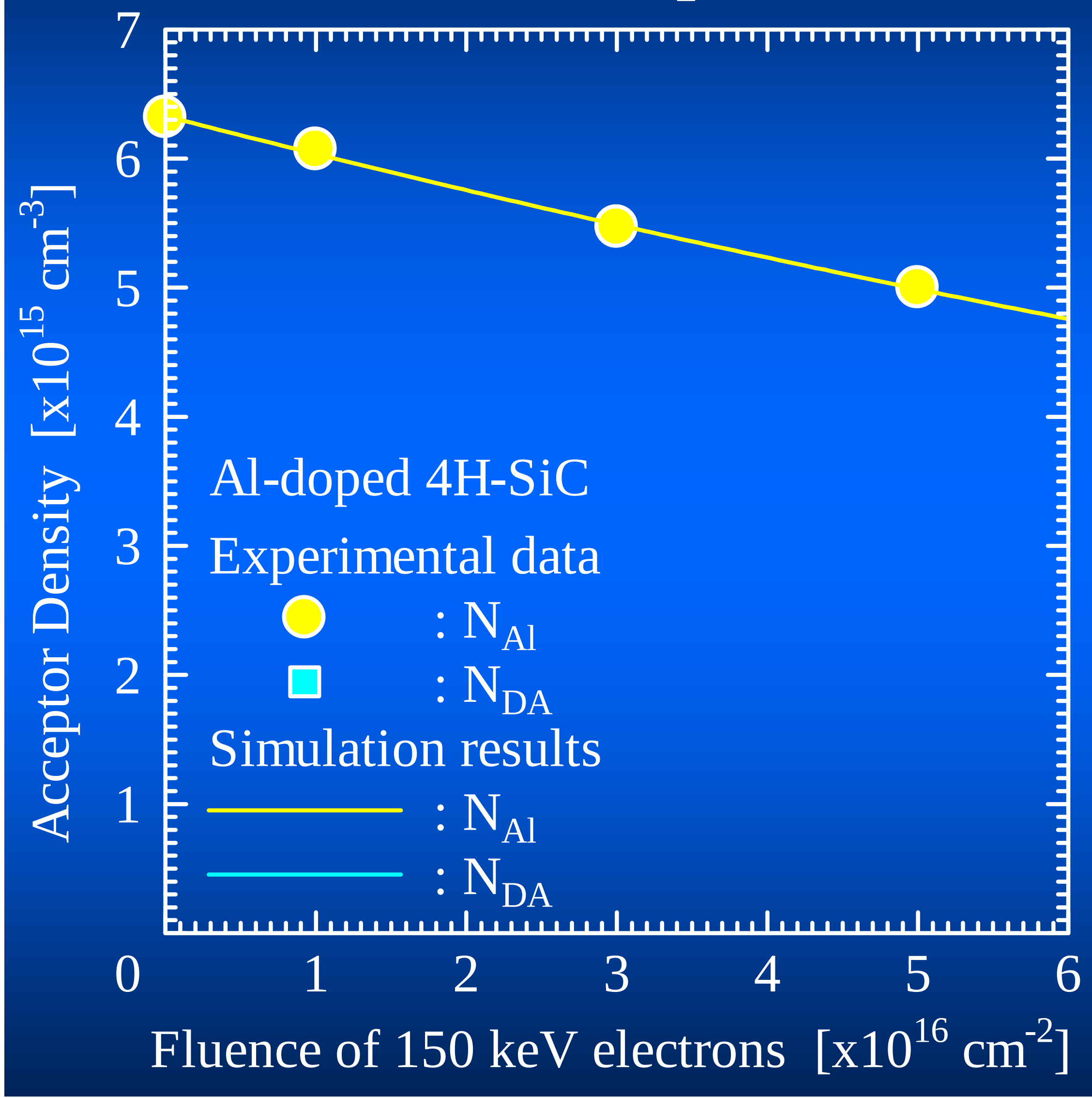
$$E_{\mathrm{DA}} = E_{\mathrm{V}} + 0.35\ \mathrm{eV}$$

$$N_{\mathrm{comp}} = 1.7\times10^{15}\mathrm{cm}^{-3}$$

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



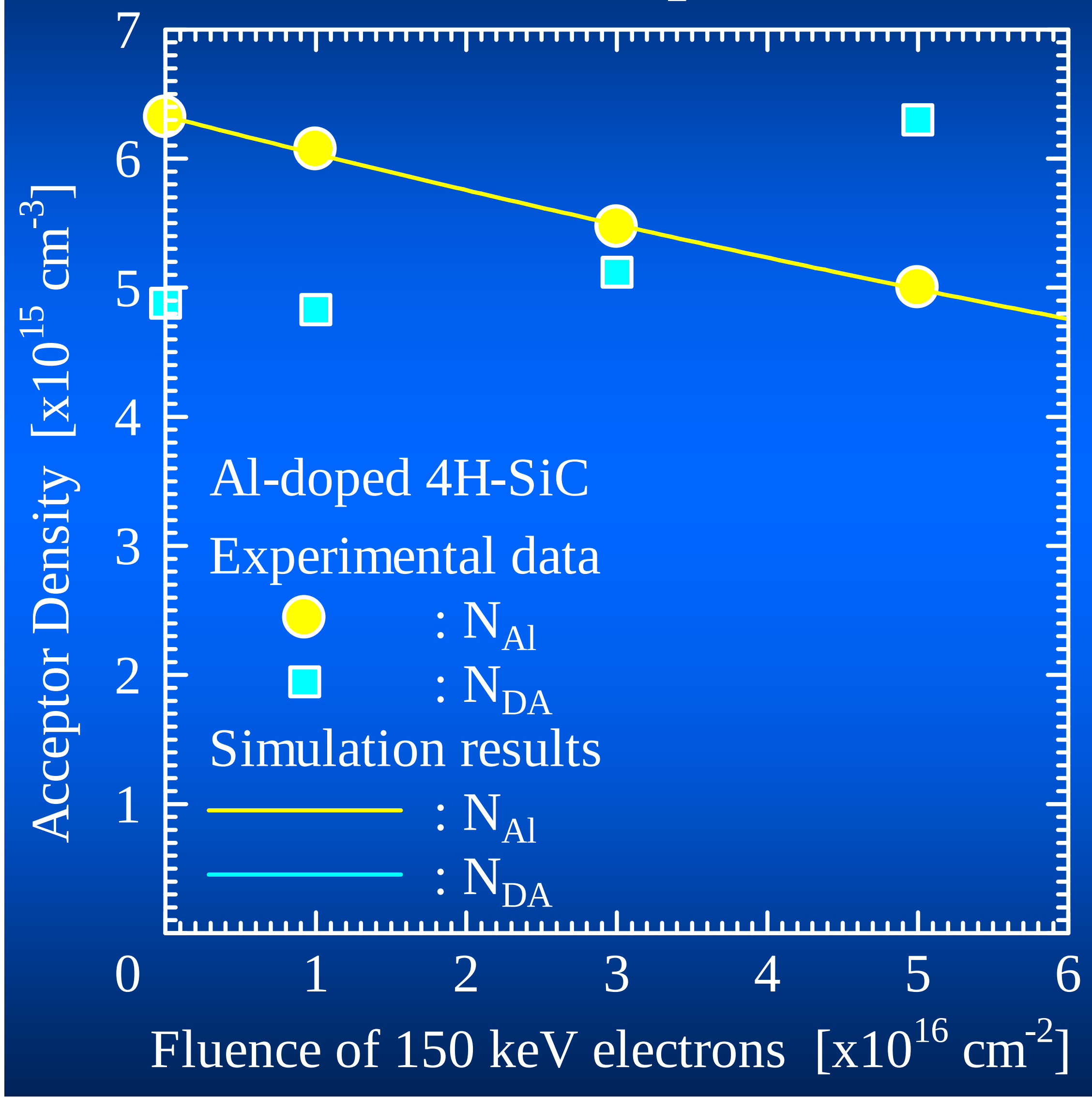
Fluence Dependence of **N_{Al}** in 4H-SiC



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

$$\kappa_{Al} = 4.8 \times 10^{-18} \ \ \mathrm{cm}^2$$

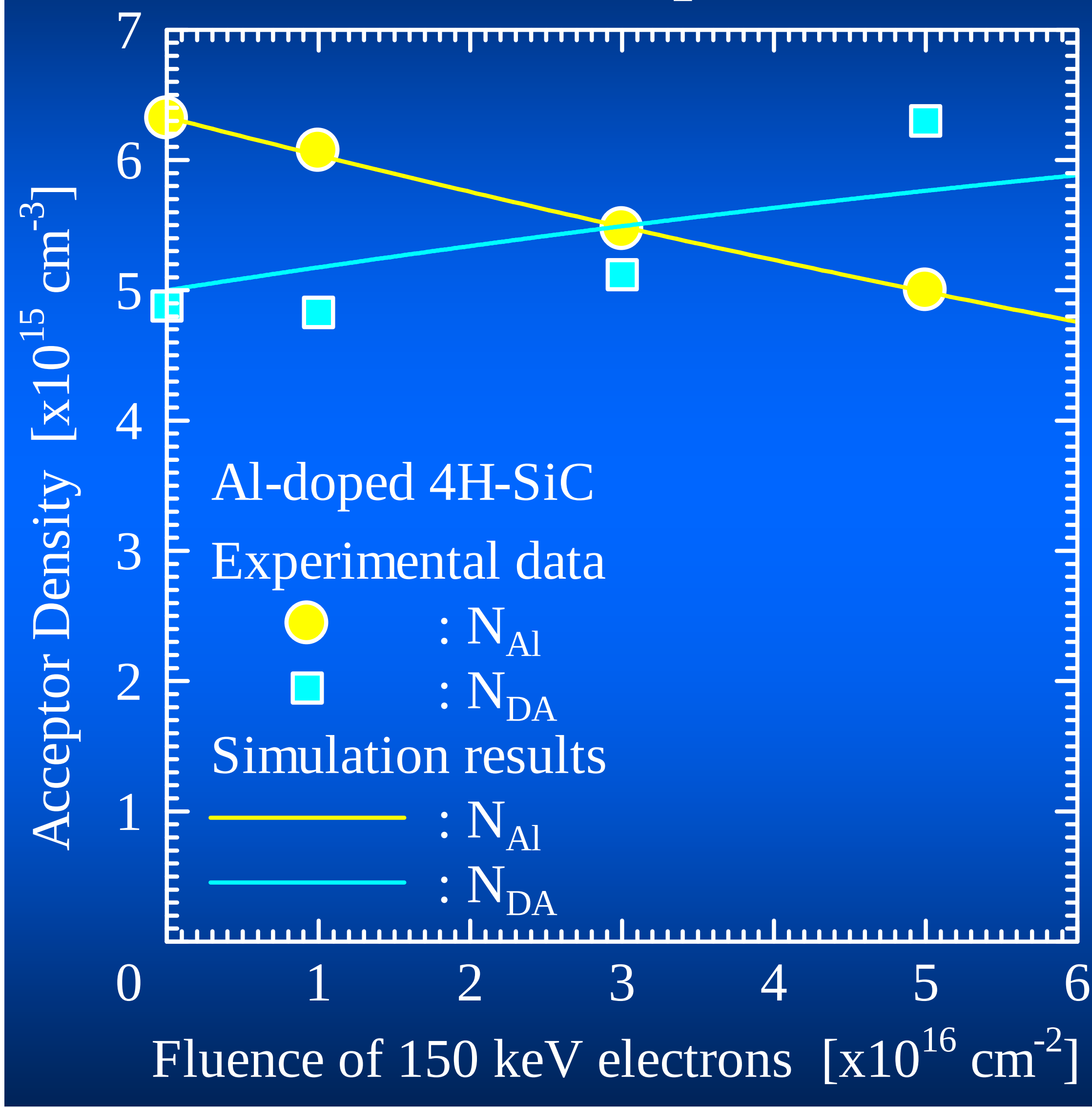
Fluence Dependence of N_{DA} in 4H-SiC



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

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

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



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

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

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

$$\kappa_{DA} = 1\times10^{-18}\ \text{cm}^2$$

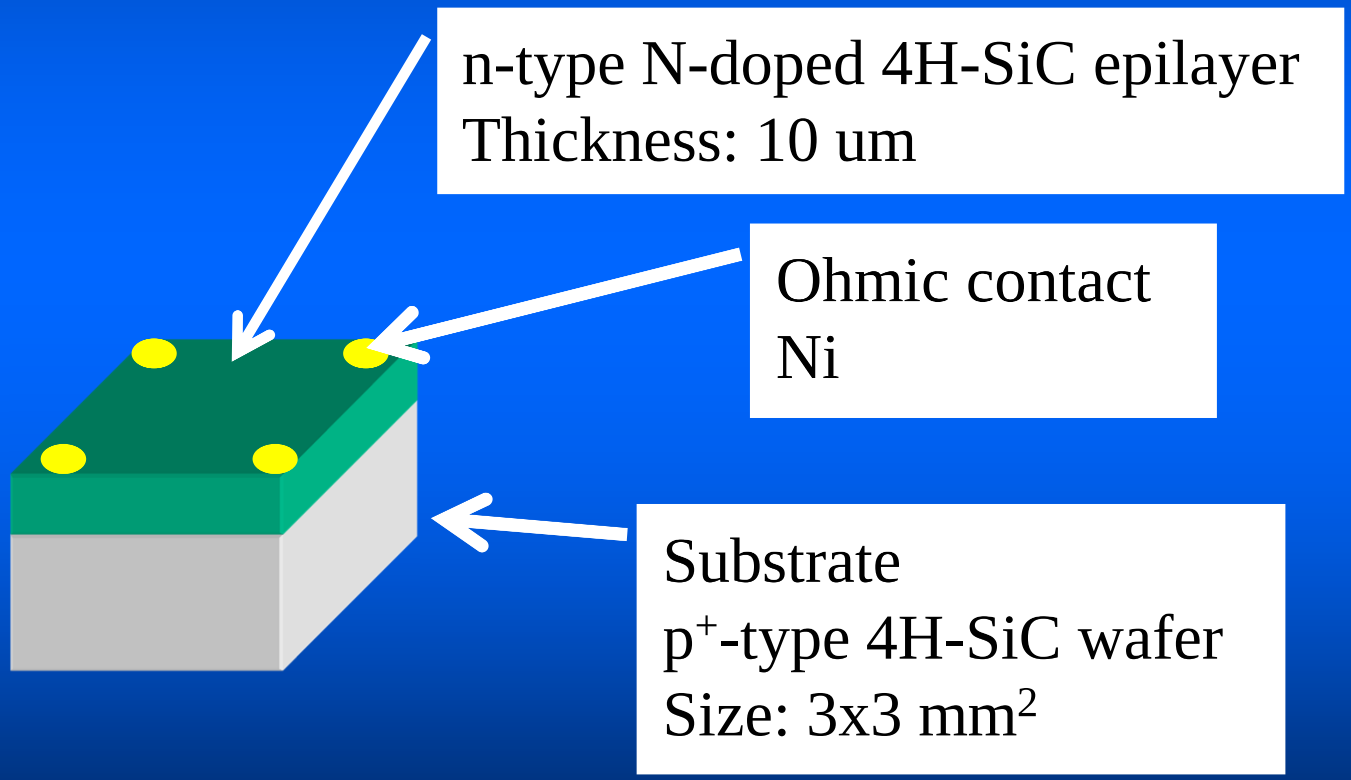
Comparison of removal cross sections for Al-doped 4H-SiC by **150** and 200 keV electron irradiation

	150 keV	**200 keV**
κ_{Al}[cm^2]	4.8×10^{-18}	4.4×10^{-17}
κ_{DA}[cm^2]	1.0×10^{-18}	1.0×10^{-17}

κ_{Al} and κ_{DA} for 150 keV electron irradiation is lower by one order than that for 200 keV electron irradiation

Sample Configuration

Investigation of donors in **N-doped 4H-SiC**
from n(T) obtained by Hall-effect measurements

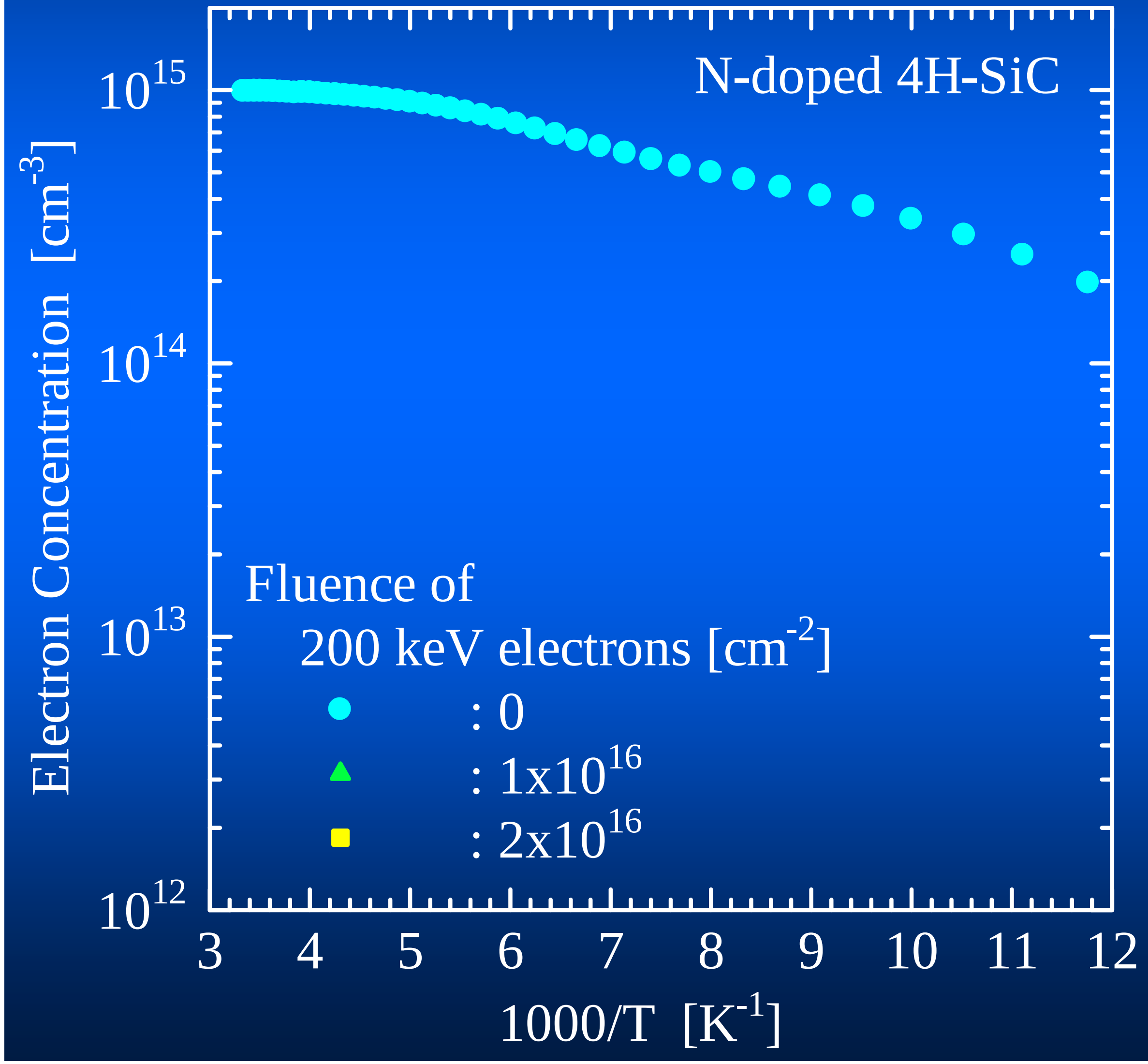


n-type N-doped 4H-SiC epilayer
Thickness: 10 um

Ohmic contact
Ni

Substrate
p^+-type 4H-SiC wafer
Size: 3x3 mm^2

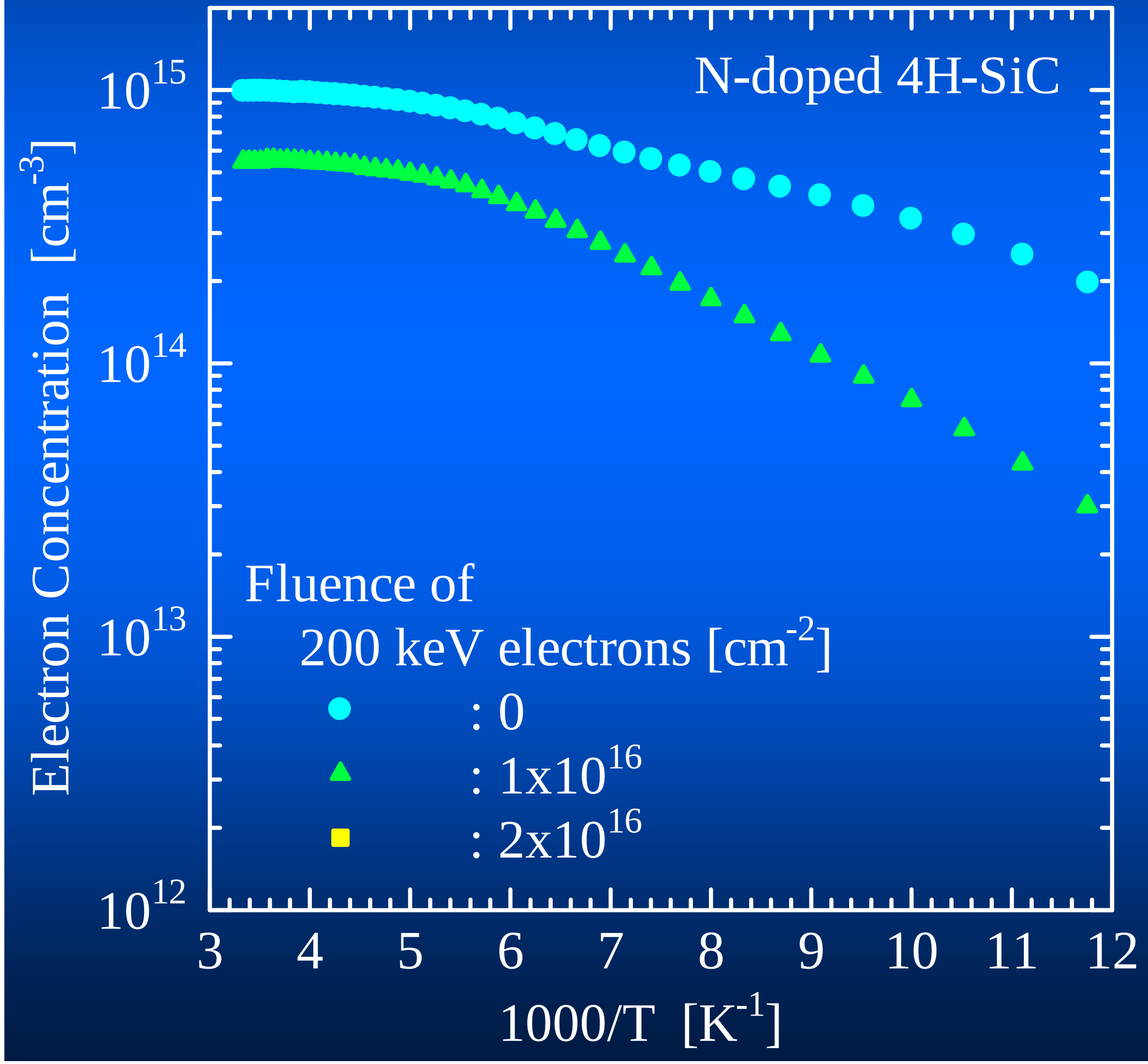
Reduction in n(T) in N-doped n-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

0

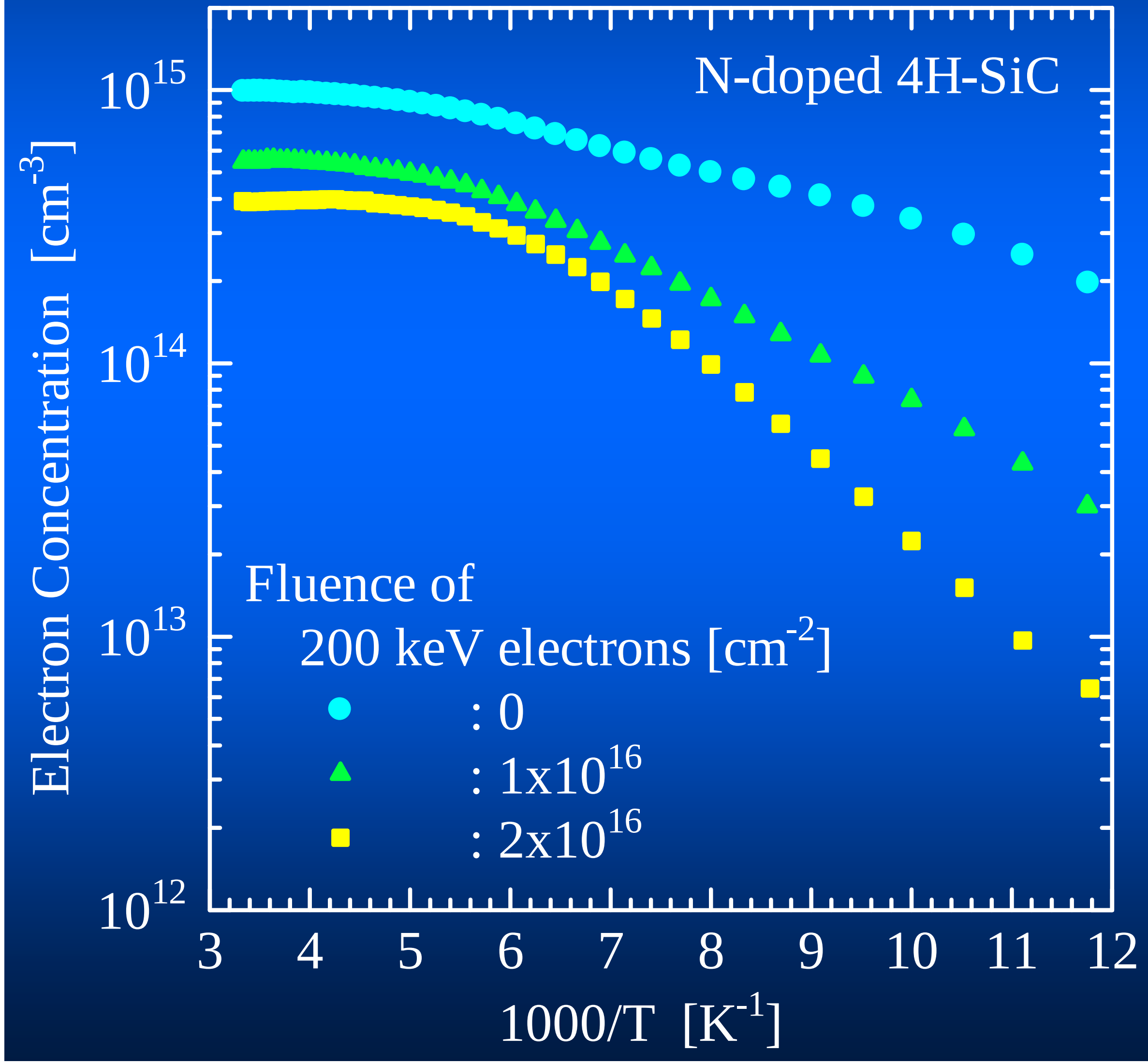
Reduction in n(T) in N-doped n-type 4H-SiC by **200 keV** electron irradiation



Fluence [cm^{-2}]

1×10^{16}

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

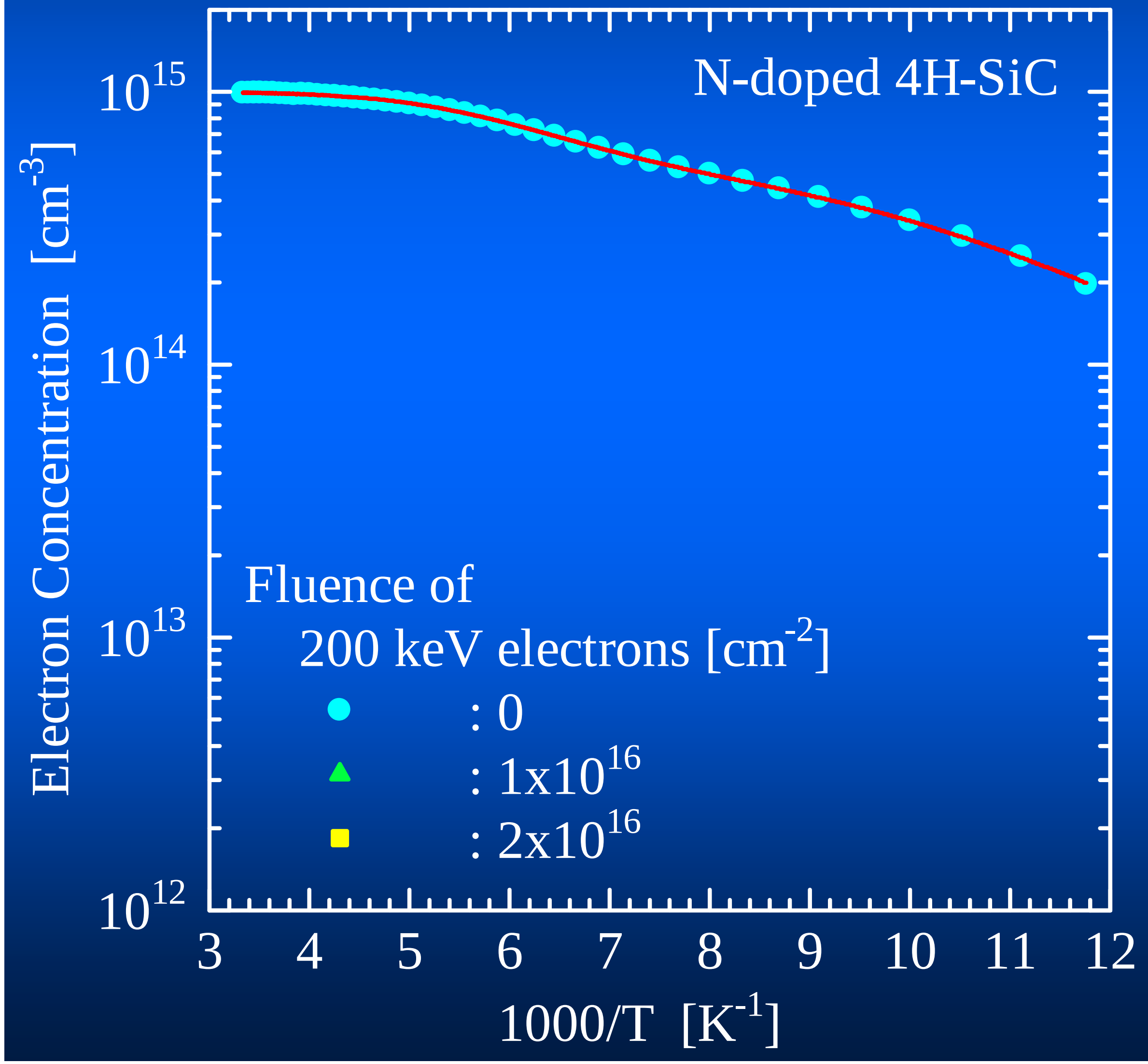


Fluence [cm^{-2}]

2×10^{16}

200 keV electron irradiation reduced n(T).

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



Fluence [cm^{-2}]

0

Simulation Result

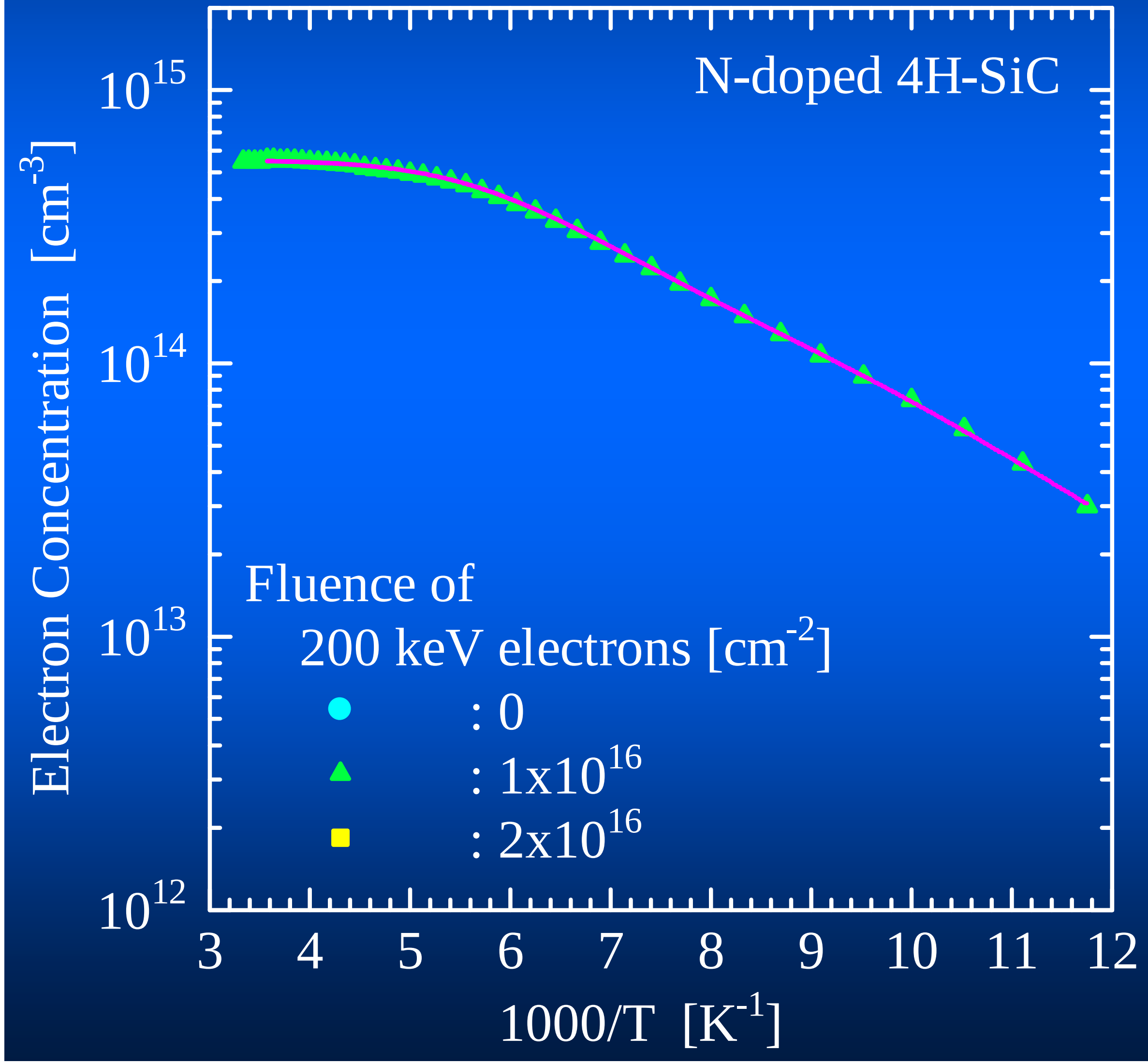
$$N_{NH} = 4.7 \times 10^{14} cm^{-3}$$

$$E_{NH} = E_C - 0.07 \text{ eV}$$

$$N_{NK} = 4.9 \times 10^{15} cm^{-3}$$

$$E_{NK} = E_C - 0.12 \text{ eV}$$

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



Fluence [cm^{-2}]

1×10^{16}

Simulation Result

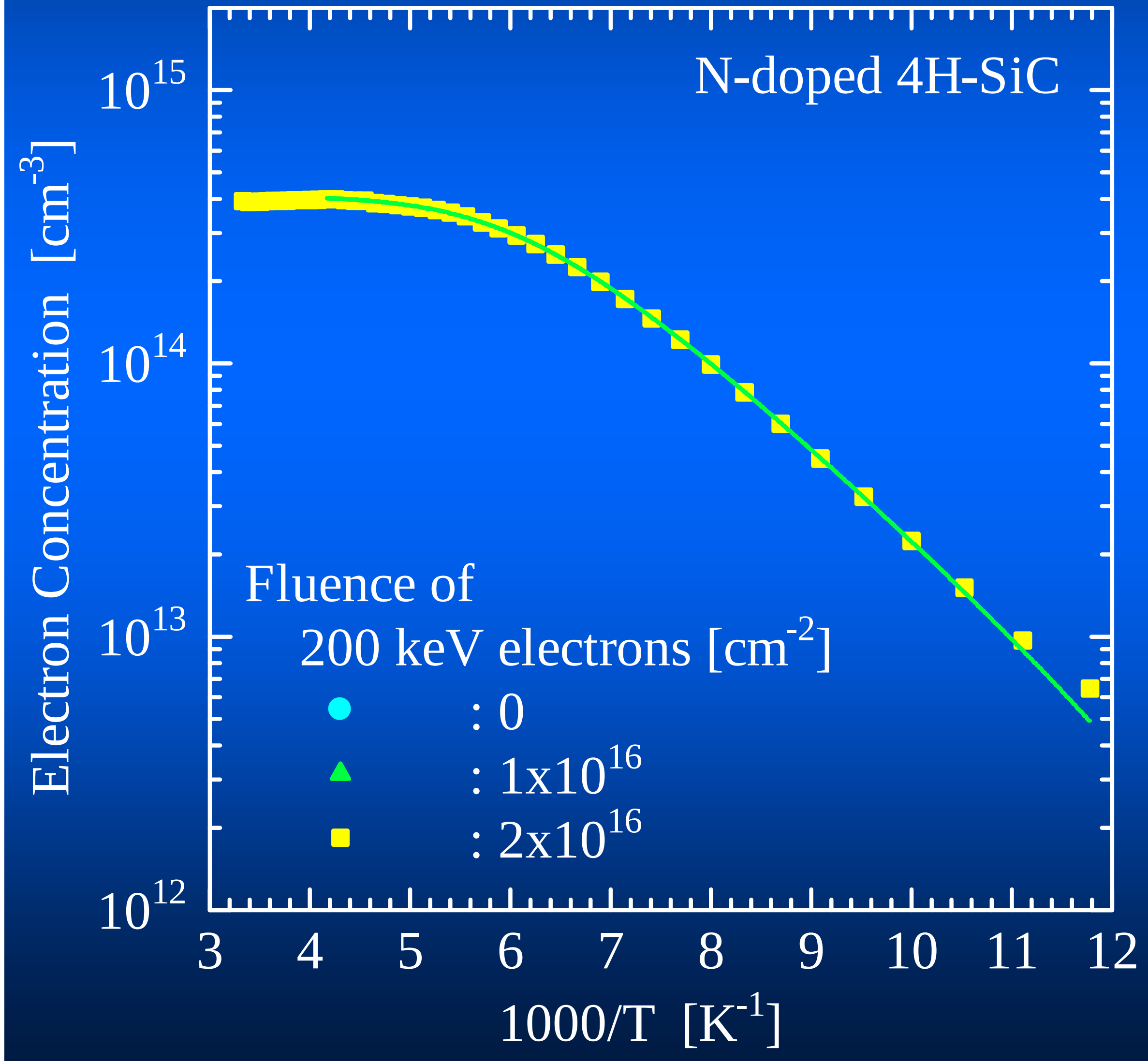
$$N_{NH} = 1.6\times10^{14}\,\mathrm{cm}^{-3}$$

$$E_{NH} = E_C - 0.09\,\mathrm{eV}$$

$$N_{NK} = 4.0\times10^{14}\,\mathrm{cm}^{-3}$$

$$E_{NK} = E_C - 0.12\,\mathrm{eV}$$

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



Fluence [cm^{-2}]

2×10^{16}

Simulation Result

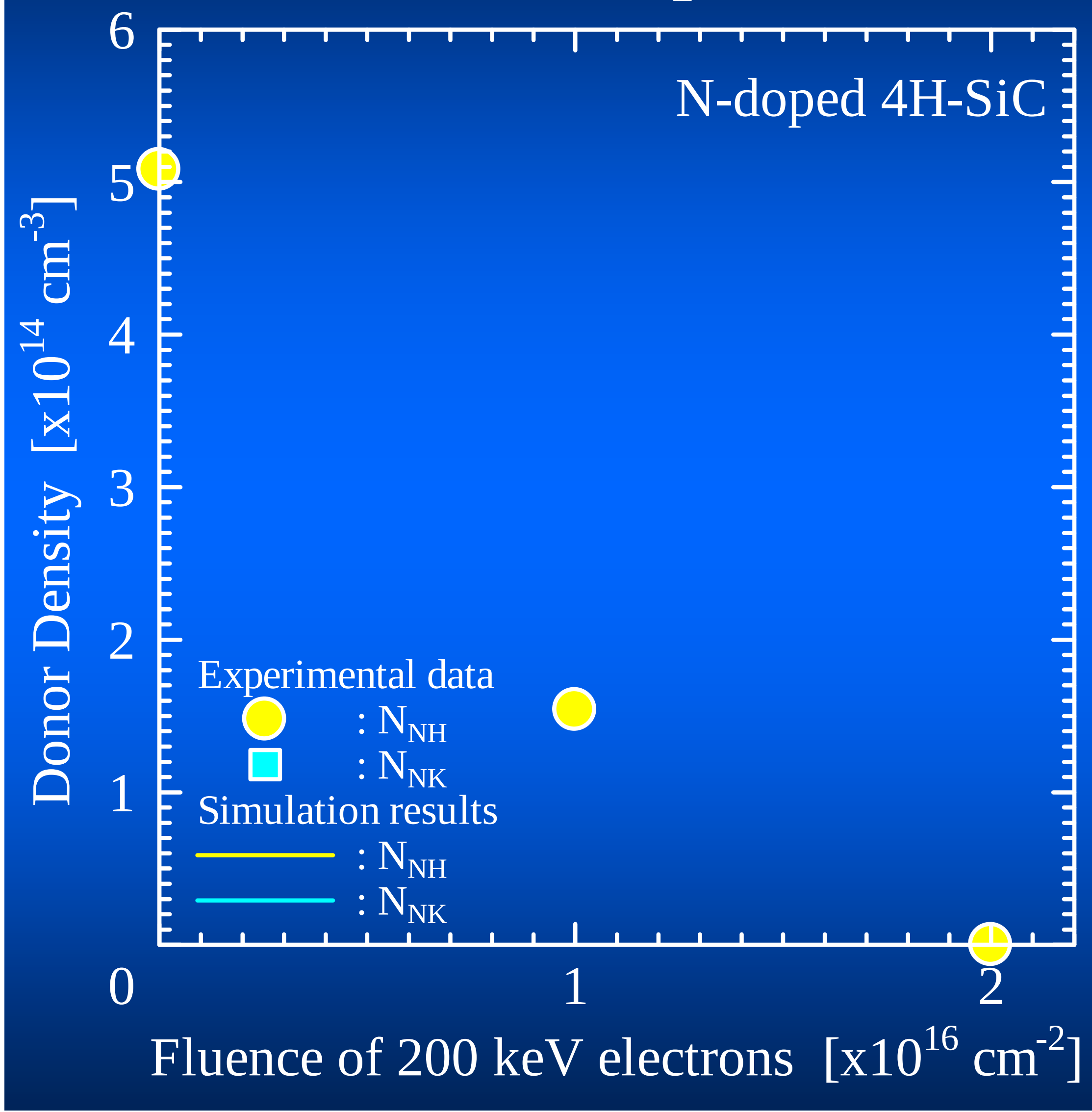
$N_{NH} < 1\times10^{13}\text{cm}^{-3}$

$E_{NH} = E_C - 0.09$ eV

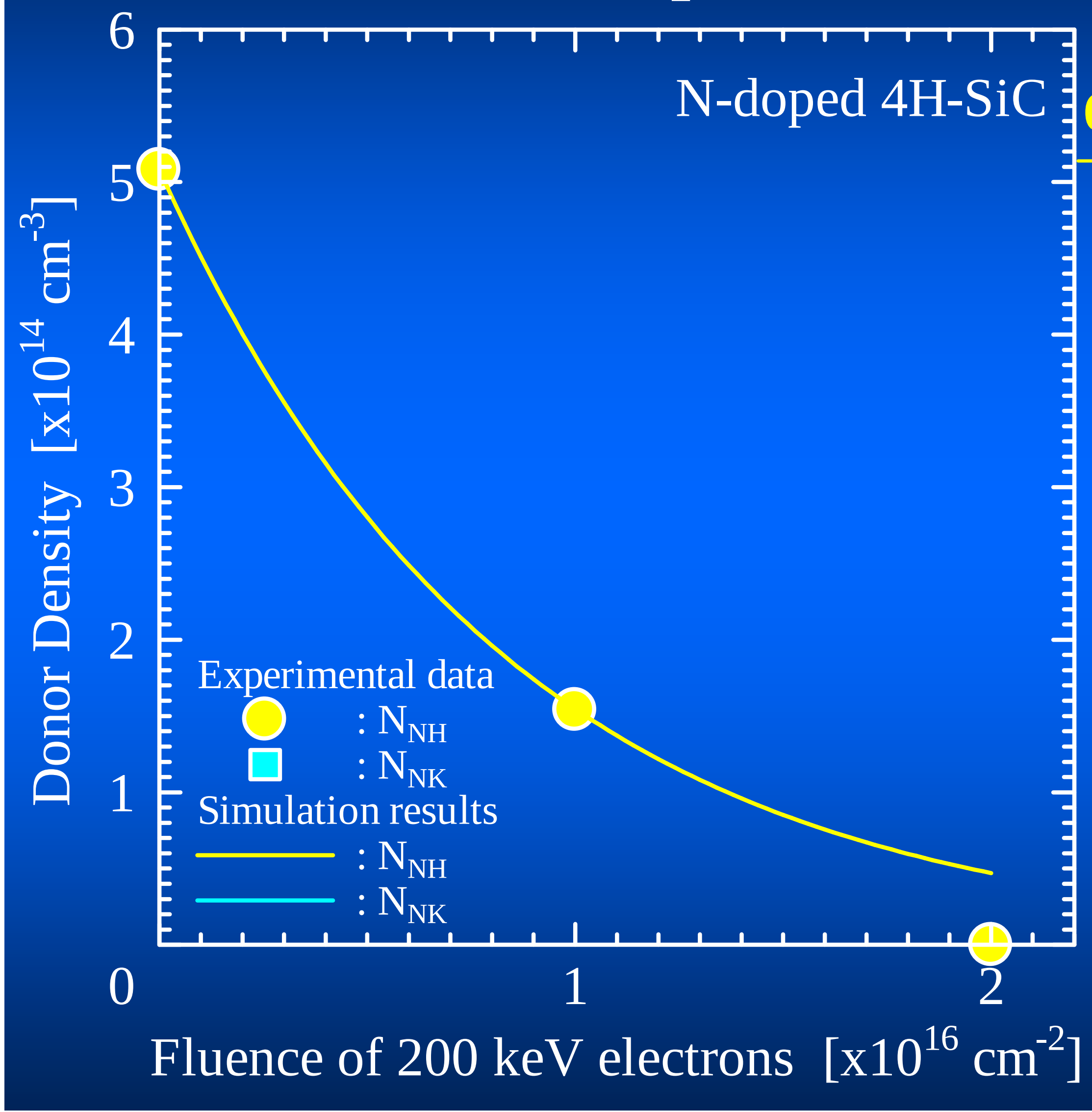
$N_{NK} = 4.1\times10^{14}\text{cm}^{-3}$

$E_{NK} = E_C - 0.12$ eV

Fluence Dependence of N_{NH} in 4H-SiC



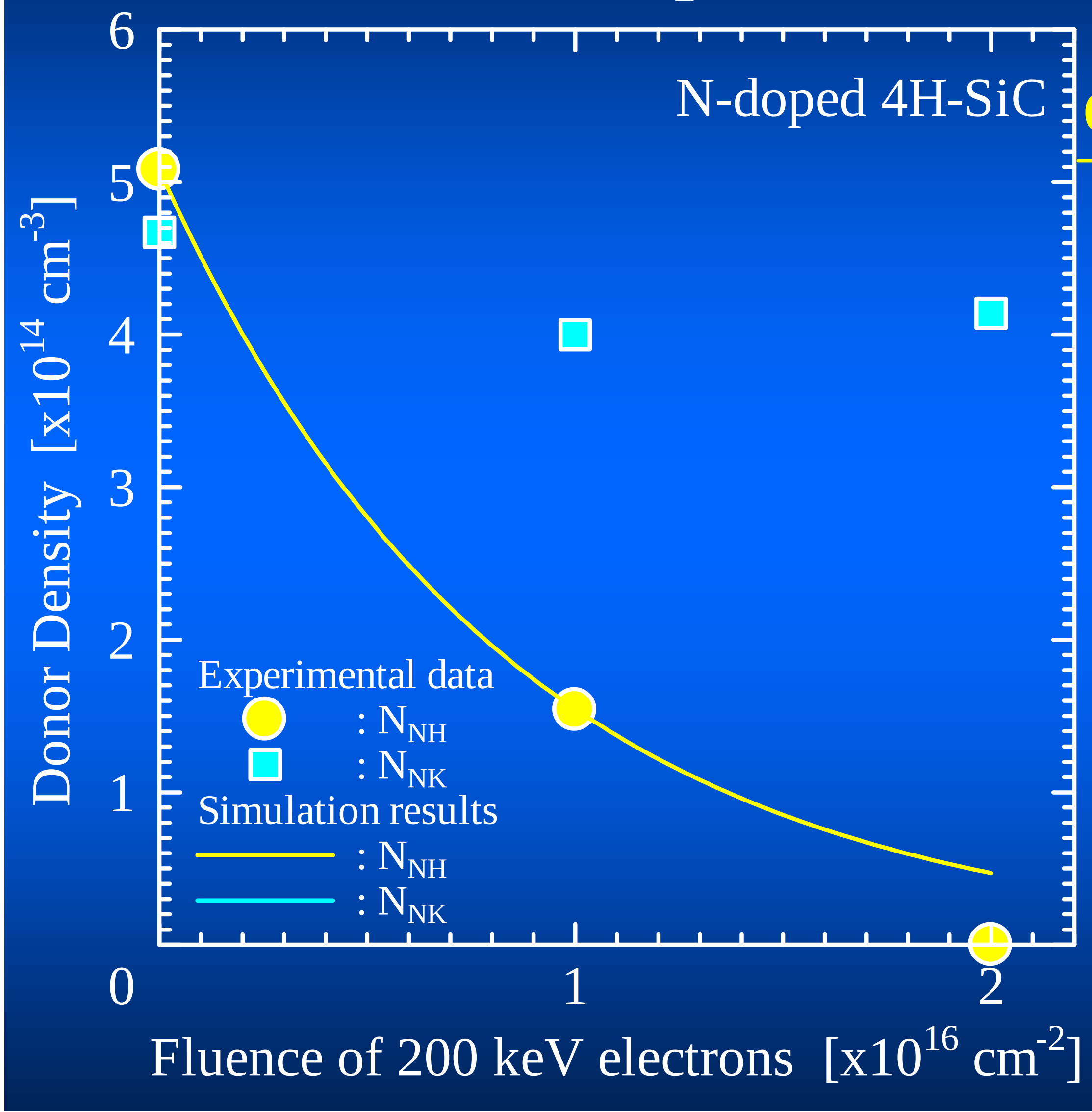
Fluence Dependence of $\mathbf{N_{NH}}$ in 4H-SiC



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

$$\kappa_{NH} = 1.2\times10^{-16}\ \text{cm}^2$$

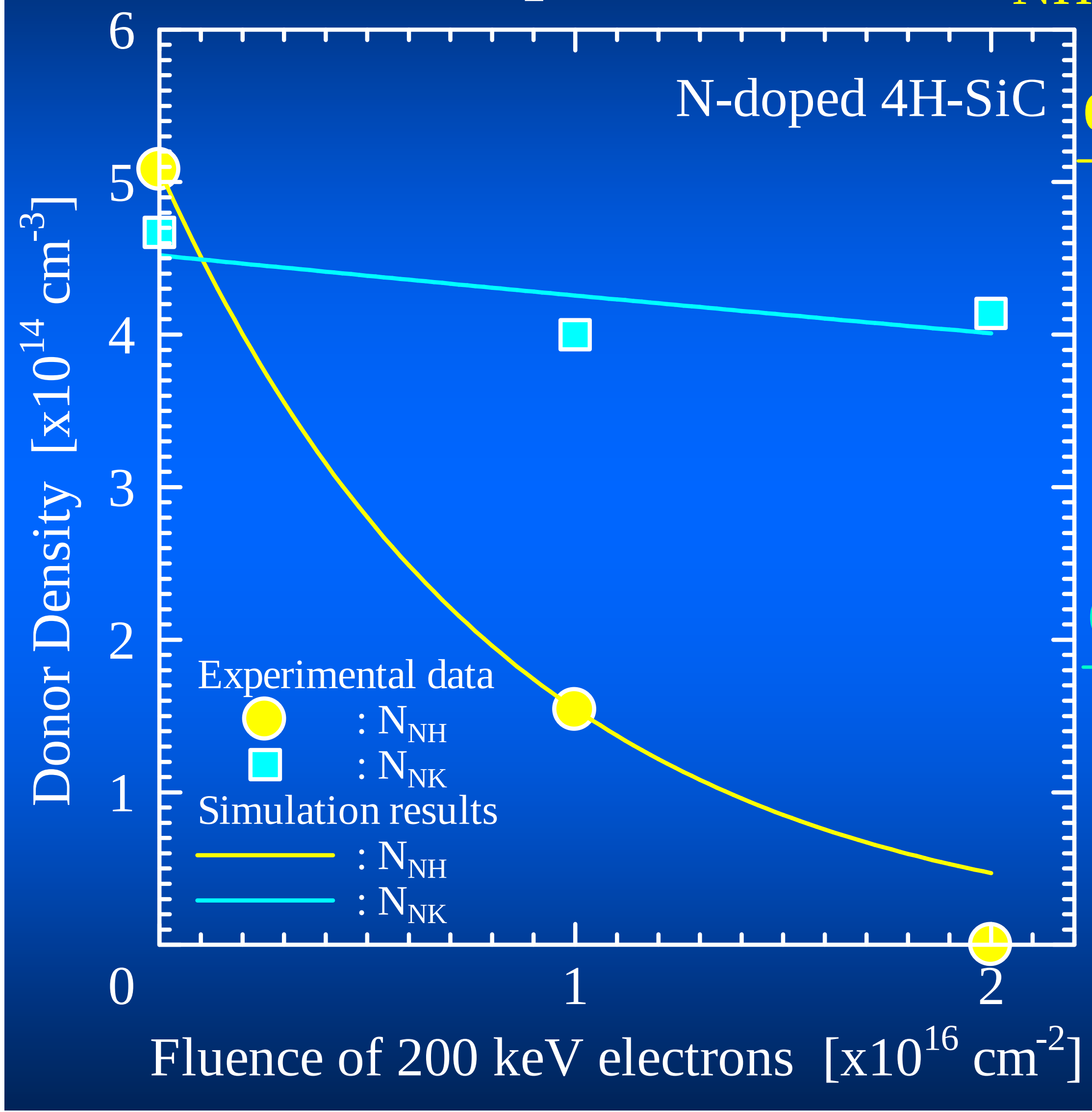
Fluence Dependence of N_{NK} in 4H-SiC



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

$$\kappa_{NH} = 1.2\times10^{-16}\ \text{cm}^2$$

Fluence Dependence of N_{NH} and N_{NK} in 4H-SiC



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

$$\kappa_{NH} = 1.2\times10^{-16}\ \text{cm}^2$$

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

$$\kappa_{NK} = 6.0\times10^{-18}\ \text{cm}^2$$

Comparison of removal cross sections for 200 keV electron irradiation of N donors located at hexagonal and cubic C-sublattice sites

	200 keV
κ_{NH} [cm^2]	1.2×10^{-16}
κ_{NK} [cm^2]	6.0×10^{-18}

N donors at hexagonal C-sublattice sites are less radiation-resistant than N donors at cubic C-sublattice sites.

Conclusion

In Al-doped p-type 4H-SiC

1. p(T) was unchanged by 100 keV electron irradiation.
2. 150 keV electron irradiation may transform Al acceptors into deep acceptors.

In N-doped n-type 4H-SiC

3. N donors at hexagonal sites are less radiation-resistant than N donors at cubic sites.