Mechanisms of reduction in hole concentration in Al-doped 4H-SiC by electron irradiation

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Abstract

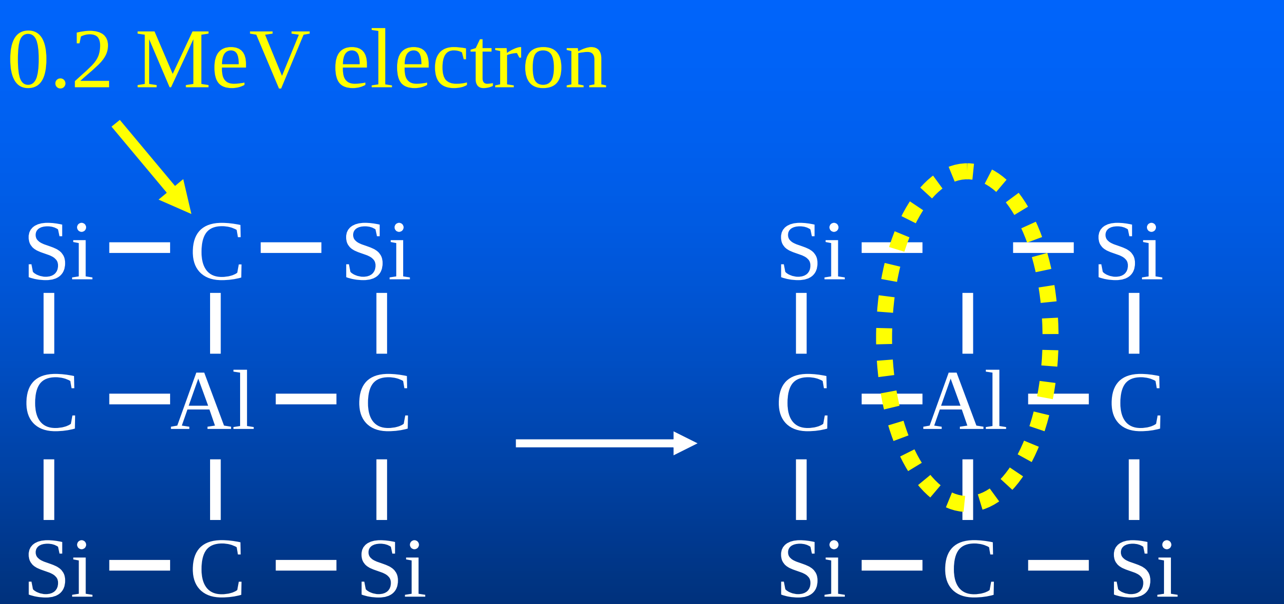
In lightly Al-doped 4H-SiC epilayers

1. Al acceptor with E_V+0.2 eV
2. unknown deep acceptor with E_V+0.36 eV

With irradiation by 0.2 MeV electrons,

1. **Al acceptor density is decreased**
2. **deep acceptor density is increased**

Model



Al acceptor　　　Al-V complex

Introduction

In unirradiated lightly Al-doped 4H-SiC

acceptor with E_V+0.2 eV → Al acceptor

acceptor with E_V+0.35 eV → ?

Both the densities are similar

With irradiation by 4.6 MeV electrons

1. Al acceptor density (N_{Al}) is reduced significantly
2. deep acceptor density (N_{Defect}) is decreased slightly

N_{Al} is decreased due to

1. the displacement of Al

or

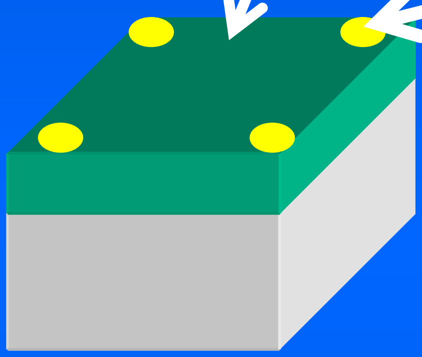
2. the bond breaking between Al and its nearest neighbor C

H. Matsuura, et al. Appl. Phys. Lett. 83 (2003) 4981.

Experiment

Al-doped 4H-SiC epilayer
Thickness: 10 um
Al-doping density: ~5×10^{15} cm^{-3}

Ohmic contact
Ti/Al

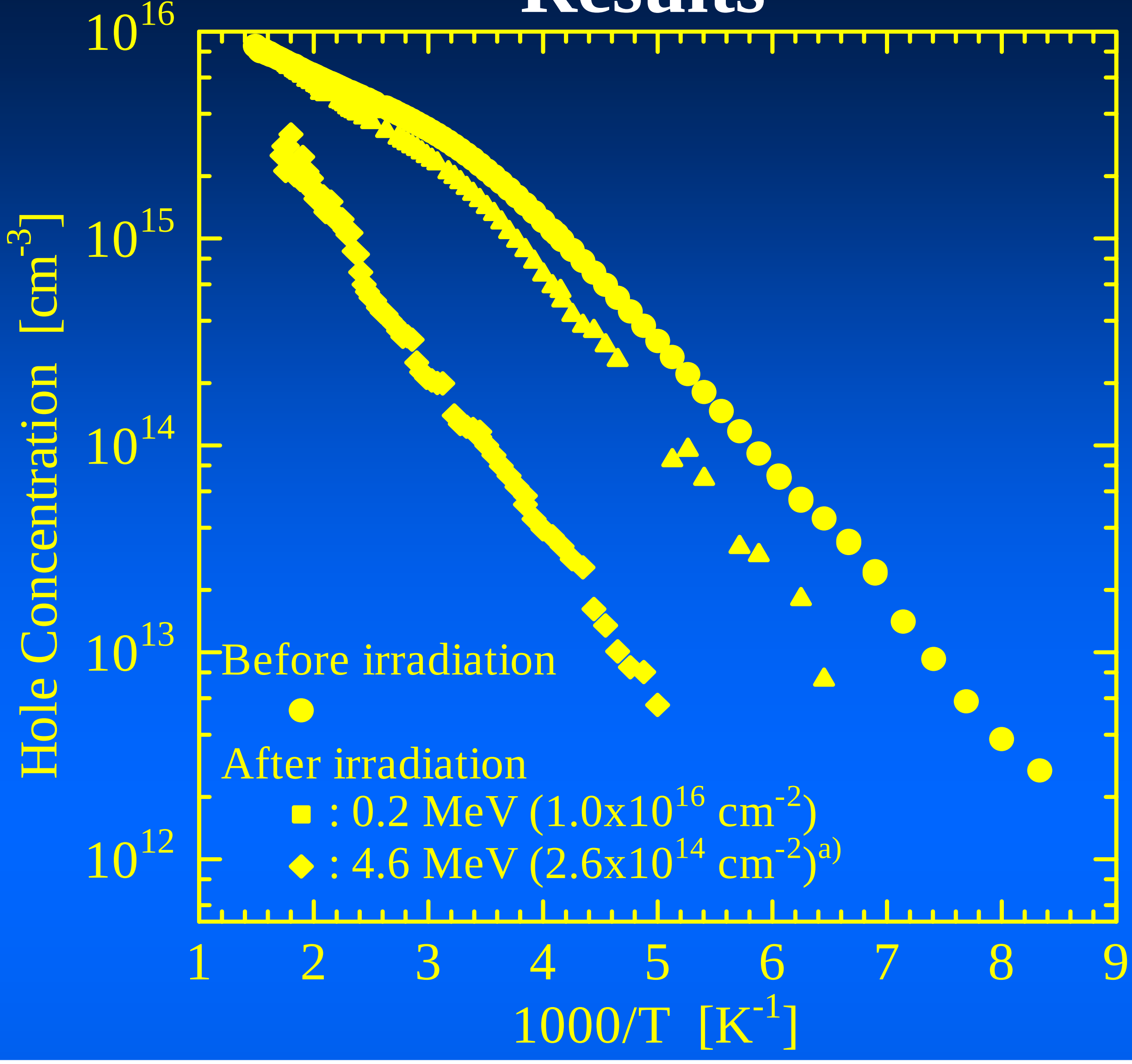


Substrate
n-type 4H-SiC wafer
Size: 1×1 cm^2
Thickness: 376 um
Resistivity: 0.02 Ohm cm

Electron irradiation
- Energy: 0.2 MeV
- Fluence: 1.0×10^{16} cm^{-2}

Hall-effect measurement
- Magnetic field: 1.4 T

Results

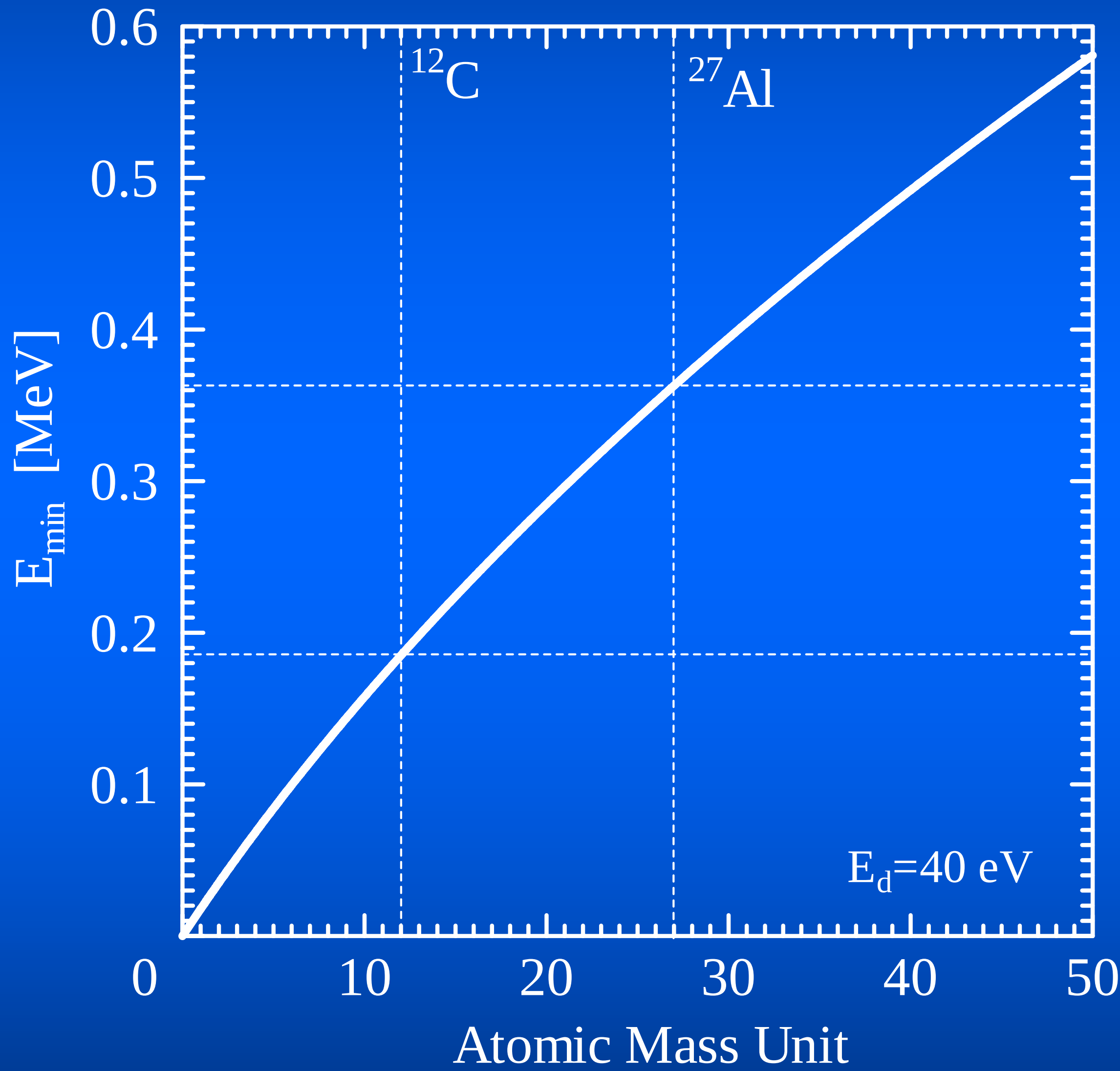


	0.2 MeV 1.0×10^{16} cm^{-2}		4.6 MeV 2.6×10^{14} cm^{-2}	
	Before	**After**	**Before**	**After**
ΔE_{Al}	203	217	203	206
N_{Al}	5.2×10^{15}	4.3×10^{15}	6.2×10^{15}	8.2×10^{14}
ΔE_{Defect}	357	363	365	383
N_{Defect}	3.5×10^{15}	5.2×10^{15}	4.2×10^{15}	3.4×10^{15}

ΔE [meV] N [cm^{-3}]

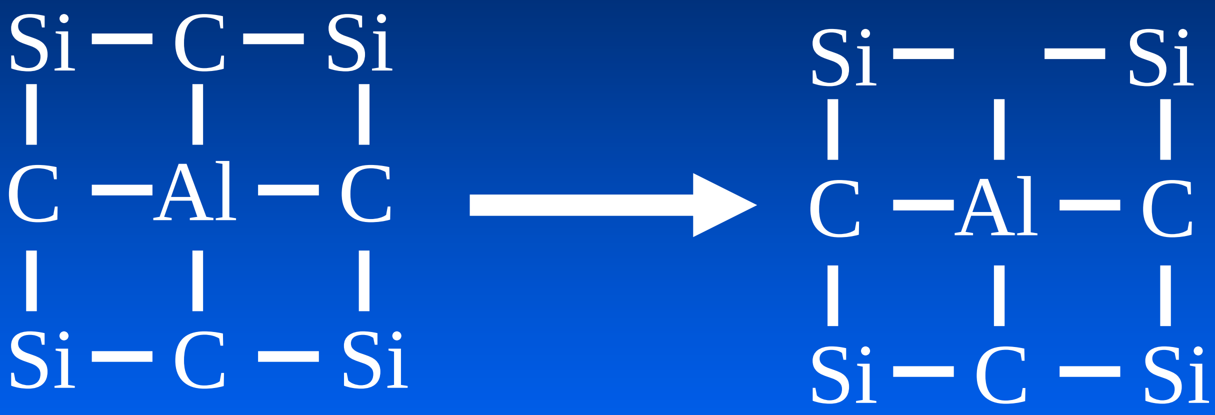
Discussion

Atomic-mass-unit dependence of minimum electron required for displacement of substitutional atom



One electron with 0.19~0.36 MeV can displace only the C atom

0.2 MeV electron irradiation



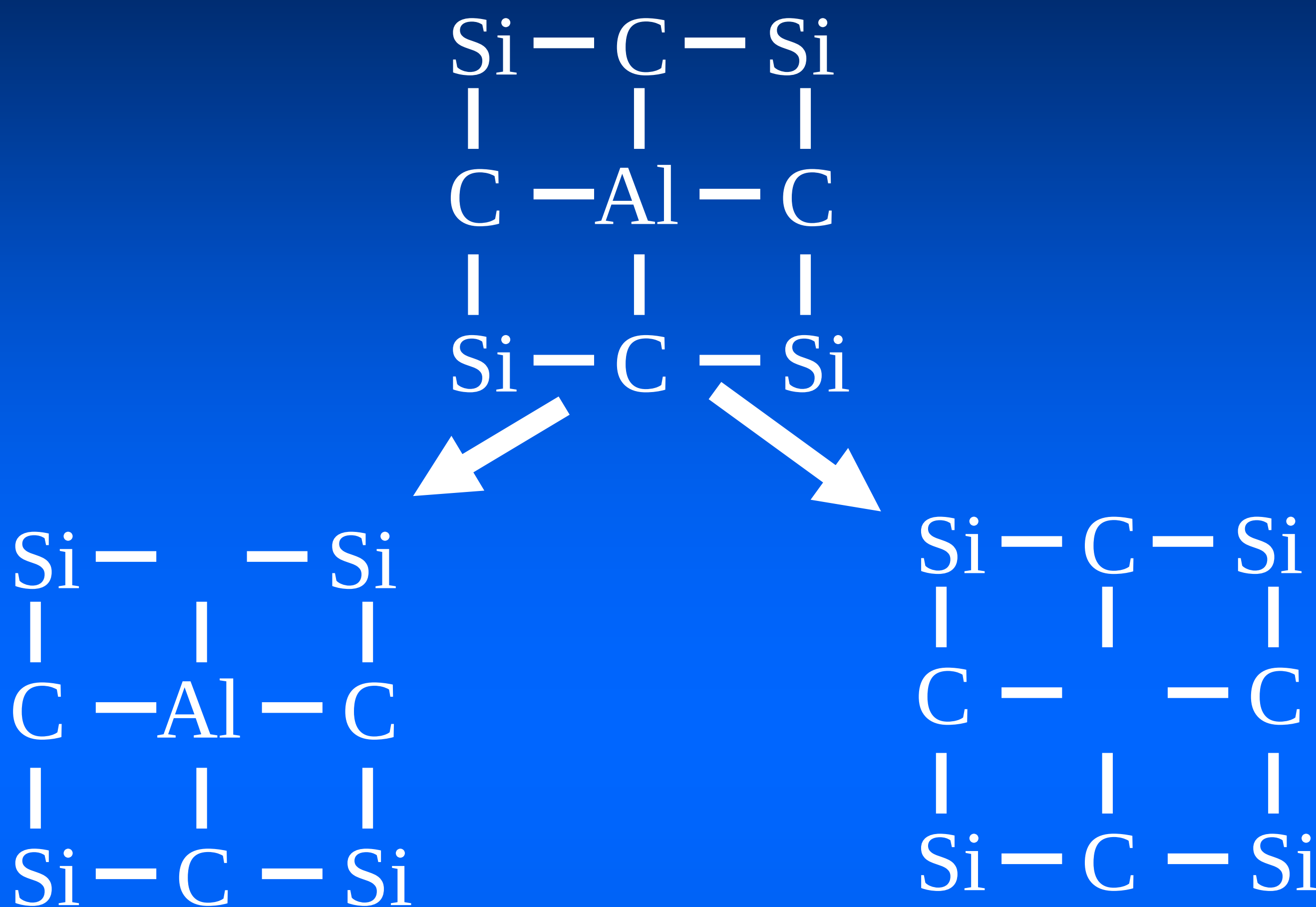
C atom is displaced ➔ Vacancy is created

1. **Al acceptor density is decreased**
2. **Al-V complex density is increased**

Since N_{Al} is decreased and N_{Defect} is increased, the deep acceptor (defect) is the most likely Al-V complex.

In the case that the defect is Al-V

4.6 MeV electron irradiation



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

1. N_{Al} is decreased

1. N_{Al} is decreased significantly

2. N_{Defect} is decreased slightly

These are in good agreement with the experimental results.

Conclusion

With 0.2 MeV electrons, the shallow Al acceptor density was decreased, while the unknown deep acceptor density was increased.

Since one 0.2 MeV electron could displace only C into an interstitial site, the Al acceptor density was deceased due to the displacement of its nearest neighbor C, which resulted in an increase in Al-V complexes.

This suggests that the unknown deep acceptor is the Al-V complex.

Appendix

Graphical peak analysis method for determining densities and energy levels of dopants and defects from the temperature dependence of majority carrier concentration.

Free Carrier Concentration Spectroscopy (FCCS)

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

The FCCS signal has a peak at the temperature corresponding to each acceptor level or defect level.
From each peak, the density and energy level of the corresponding acceptor or defect can be determined accurately.

Papers for FCCS

1. Si irradiated with electrons or protons

- Evaluation of Hole Traps in 10-MeV Proton-Irradiated p-Type Silicon from Hall-Effect Measurements
  Jpn. J. Appl. Phys. 37 (1998) 6034-6040.
- Temperature dependence of electron concentration in type-converted silicon by $1x10^{17}$ cm^{-2}-fluence irradiation of 1-MeV electrons
  Appl. Phys. Lett. 76 (2000) 2092-2094.

2. Undoped GaSb

- Acceptor Densities and Acceptor Levels in Undoped GaSb Determined by Free Carrier Concentration Spectroscopy
  Jpn. J. Appl. Phys. 41 (2002) 496-500.

3. Te-doped $Al_{0.6}Ga_{0.4}Sb$

- Ionization of deep Te donor in Te-doped $Al_{0.6}Ga_{0.4}Sb$ epilayers
  J. Appl. Phys. 97 (2005) 093711-1 – 7.

Papers for FCCS

4. Mg-doped GaN

- Influence of excited states of Mg acceptors on hole concentration in GaN
  phys. stat. sol. C 0 (2003) 2214-2219.

5. SiC

- Nitrogen Donor Concentrations and Its Energy Levels in 4H-SiC Uniquely Determined by a New Graphical Method Based on Hall-Effect Measurement
  Jpn. J. Appl. Phys. 38 (1999) 4013-4016.
- Determination of Donor Densities and Donor Levels in 3C-SiC Grown from $Si_2(CH_3)_6$ Using Hall-Effect Measurements
  Jpn. J. Appl. Phys. 39 (2000) 5069-5075.
- Occupation probability for acceptor in Al-implanted p-type 4H-SiC
  J. Appl. Phys. 94 (2003) 2234-2241.
- Decrease in Al acceptor density in Al-doped 4H-SiC by irradiation with 4.6 MeV electrons
  Appl. Phys. Lett. 83 (2003) 4981-4983.

Papers for FCCS

- Investigation of a distribution function suitable for acceptors in SiC
  J. Appl. Phys. 95 (2004) 4213-4218.
- Dependence of acceptor levels and hole mobility on acceptor density and temperature in Al-doped p-type 4H-SiC epilayers
  J. Appl. Phys. 96 (2004) 2708-2715.
- Parameters required to simulate electric characteristics of SiC devices for n-type 4H-SiC
  J. Appl. Phys. 96 (2004) 5601-5606.
- Determination of densities and energy levels of donors in free- standing undoped 3D-SiC epilayers with thicknesses of 80 μm
  J. Appl. Phys. 96 (2004) 7346-7351.

6. p-type wide band gap semiconductors

- The influence of excited states of deep dopants on majority-carrier concentration in a wide-bandgap semiconductor
  New J. Phys. 4 (2002) 12.1-12.15.