Wide Bandgap Semiconductor Research at Mississippi State University

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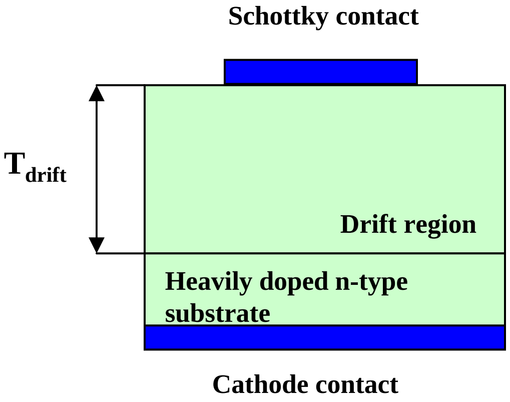
Presentation Outline

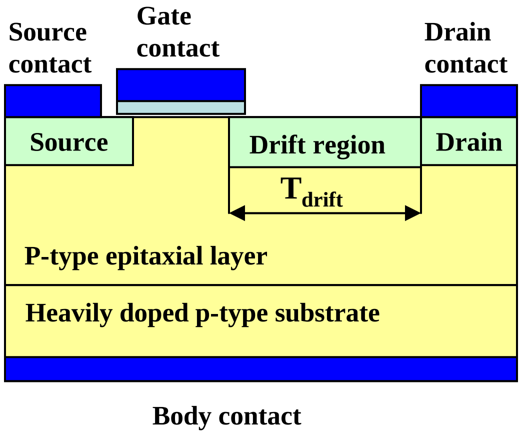
1. **Why SiC?**
2. History of SiC program at MSU
3. Advancements in SiC epitaxial growth
4. Recombination Induced Defect Reactions involving hydrogen in SiC.

SiC Material Properties (comparing to other semiconductors)

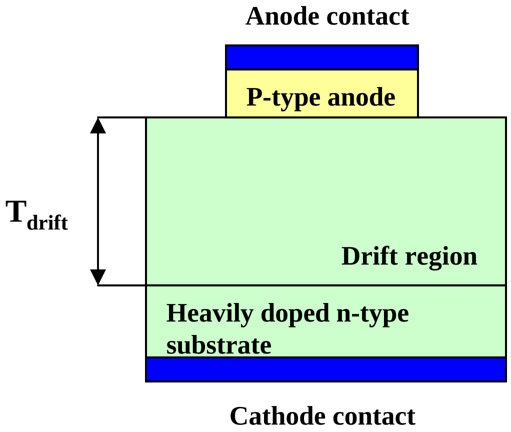
Property\Material	4H-SiC	6H-SiC	GaN	Si	GaAs
Thermal conductivity [W/cm*K]	4.9	4.9	1.3	1.3	0.55
Bandgap [eV]	3.26	3.0	3.39	1.1	1.4
Saturation drift velocity [10^5m/s]	2	2	2.5 (pick)	1	2 (pick)
Low field electron mobility (300^oK, 1e16cm^{-3}) [cm^2/V*s]	980 (Π) 865 (⊥)	81 (Π) 405 (⊥)	~ 900	1224	6555
Dielectric constant	9.7	10	9.0	11.8	12.8
Critical electric field [MV/cm]	~ 3	> 2.4	~ 3	0.3	0.4
Direct/Indirect Bandgap	I	I	D	I	D
Commercially available substrates	4”	3”	n/a	12”	8”

Drift region resistance





$$R_{drift\ sp} = \frac{T_{drift}}{q\mu_n N_{drift}}$$



$$R_{drift\ sp} = \frac{T_{drift}}{q\mu_n N_{drift} + \dfrac{(\mu_n + \mu_p) J_F \tau_a}{T_{drift}}}$$

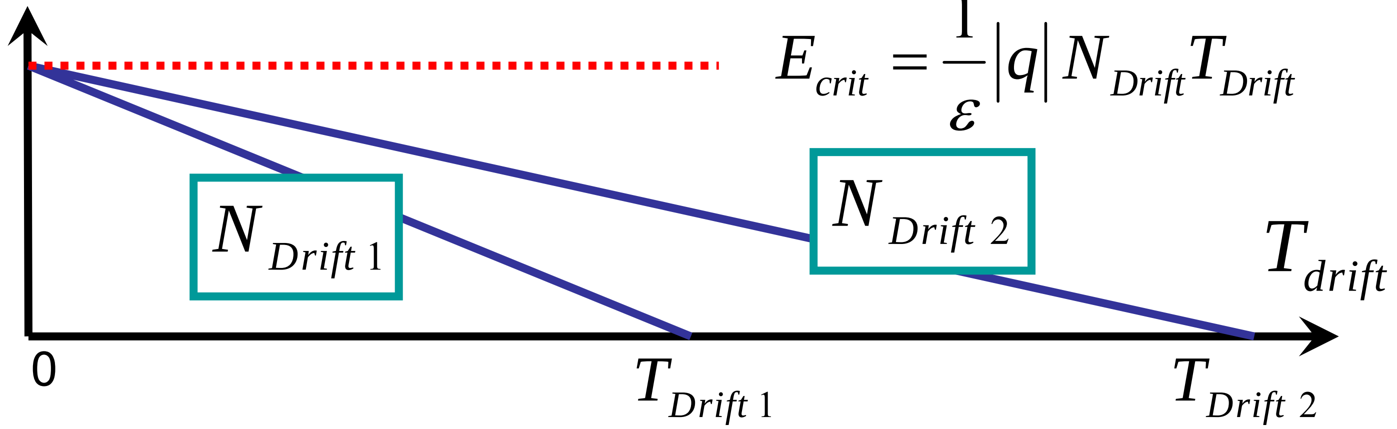
Drift region blocking capability
(1-D approach)

Voltage drop on drift region is given by: $U_{Blocking} = \int_0^{T_{Drift}} E(x)dx$

To find $E(x)$, solve the Poisson equation $div(\varepsilon \nabla \varphi) = -\rho$,

assuming free carrier concentration to be negligible (no leakage current) for non-”punch-through” layer:

$$|E| = \left|\frac{d\varphi}{dx}\right| = \left|-\frac{1}{\varepsilon}\rho x\right| = \frac{1}{\varepsilon}|q| N_D x$$



$$E_{crit} = \frac{1}{\varepsilon}|q| N_{Drift} T_{Drift}$$

Drift region blocking capability (1-D approach)

Voltage drop on drift region is given by: $U_{Blocking} = \int_{0}^{T_{Drift}} E(x)dx$

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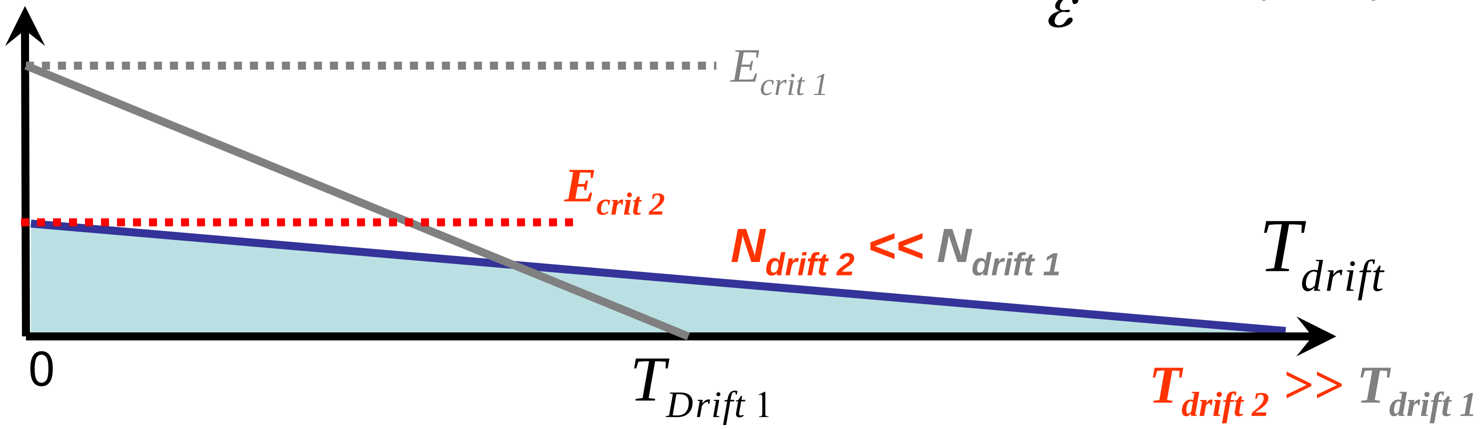
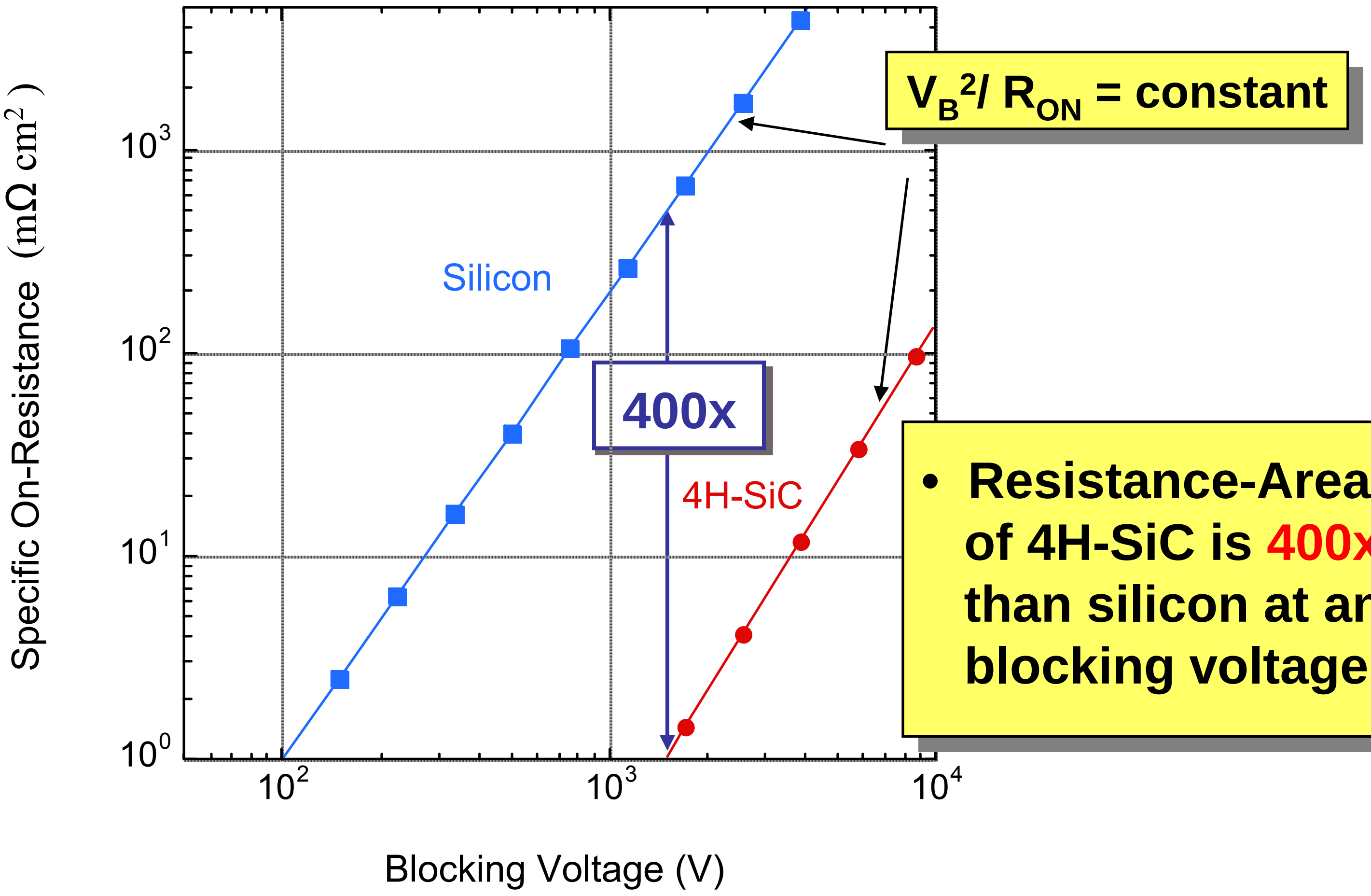
$$|E| = \left|\frac{d\varphi}{dx}\right| = \left|-\frac{1}{\varepsilon}\rho x\right| = \frac{1}{\varepsilon}|q|N_D x \qquad E_{crit} = \frac{1}{\varepsilon}|q|N_{Drift}T_{Drift}$$



Advantages of wide bandgap

Specific on-resistance of SiC

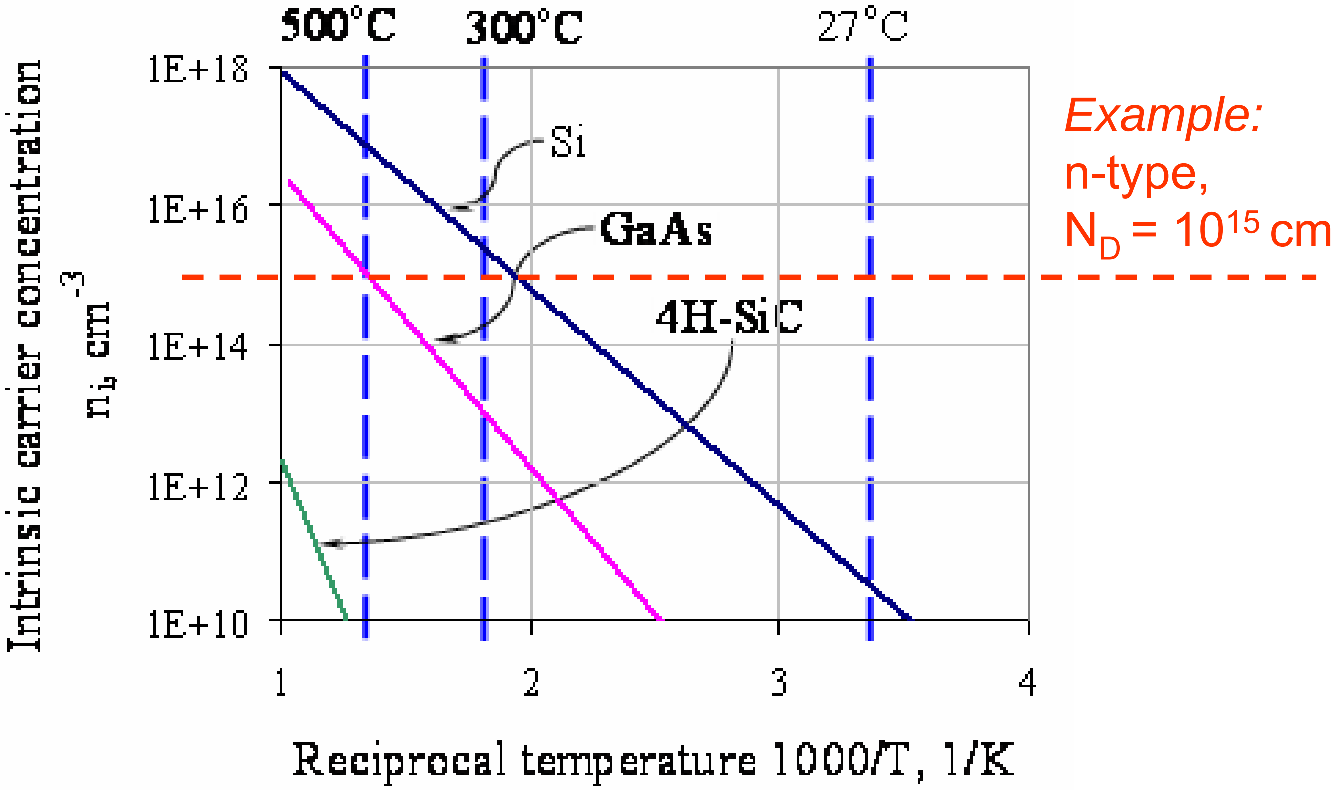


V_B^2/ R_{ON} = constant

- **Resistance-Area product of 4H-SiC is 400x lower than silicon at any given blocking voltage**

Advantages of wide bandgap

Intrinsic carrier concentration



Example:

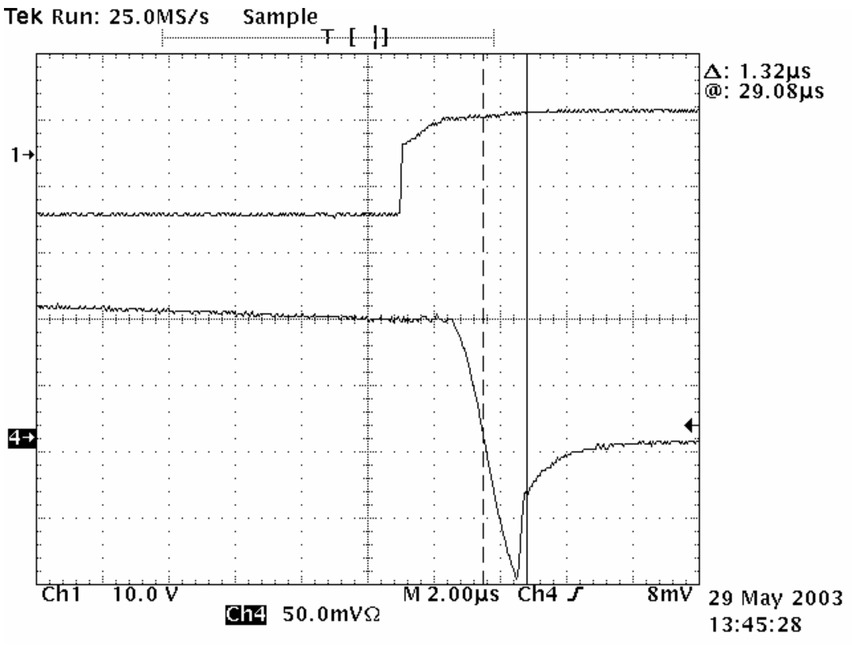
n-type,

$N_D = 10^{15}$ cm^{-3}

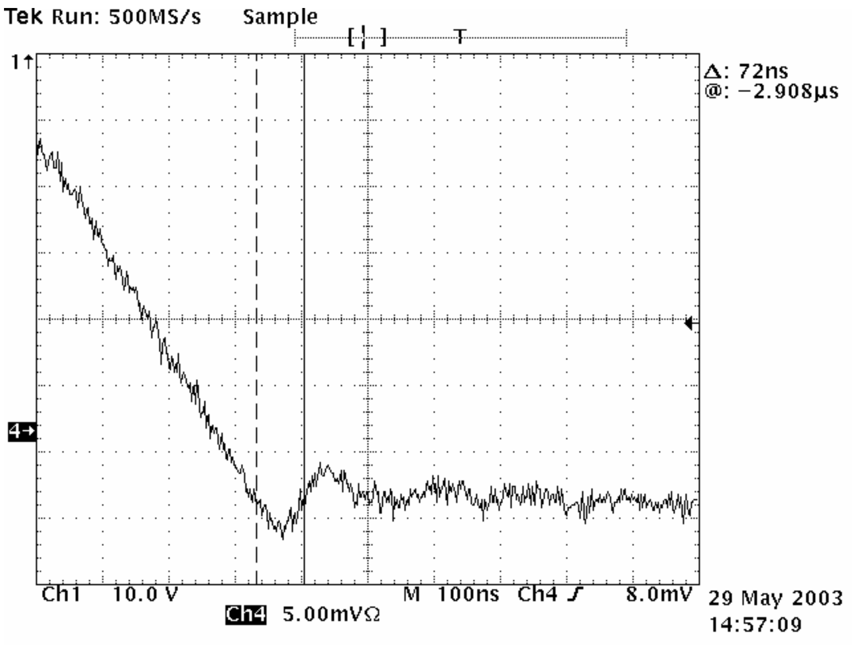
Advantages in Switching Characteristics

600 V diode recovery comparison

Si pin diode – 1.32 μs



SiC Schottky diode – 72 ns



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History of Wide Band Gap Semiconductors at Mississippi State University

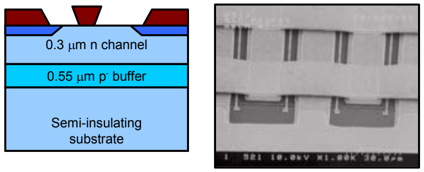
Materials - Devices- Circuits - Systems

Emerging Materials Research Laboratory
EMRL

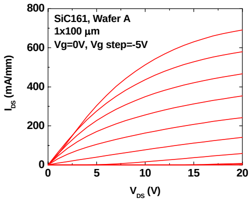
ONR
N00014-01-C-0167
C. Wood

SiC Epi at MSU

MESFET Fab at GE



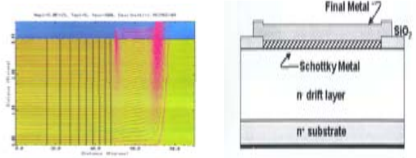
Testing at GE & MSU



Miss. Center for Advanced Semiconductor Prototyping
MCASP

AFRL/MDA
F33615-01-D-2103
J. Scofield

SiC SBD Design



SBD Fab at MSU

Commercial Packaging

Power Electronics Prototyping / Power Component Test Bed
PEP/PCT

SMDC
DASG60-00-C-0074
L. Riley

Modify HMMWV at MSU

Prototype Power Electronics at MSU

Sentinel Demo by MSU/Guard/ SMDC

Leveraging Basic Research into Production -

Rapid, economical transfer of government sponsored technology development into systems

www.ece.msstate.edu/mcasp

SEMISOUTH
LABORATORIES

Component Production

- ***Mississippi Small Business***
- **SBIR's**

EMRL

- **SiC CVD Epi Research**
- **Defect Engineering**
- **Materials Characterization**
- **Device Design**

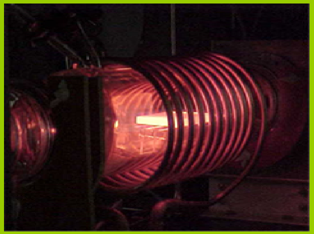
MCASP

Mississippi Center for Advanced Semiconductor Prototyping

- **Multi Wafer SiC Epi**
- **Sub-micron lithography**
- **Multi Wafer Plasma Etching**
- **Multi Wafer PECVD**
- **Multi Wafer Metal Deposition**

Material Science Program at MSU

ONR, AFRL, SBIR/STTR…



Novel epitaxial growth techniques

PL

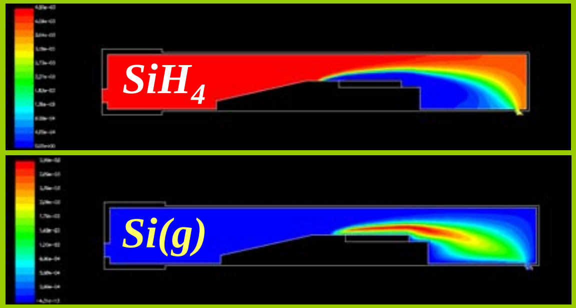
DLTS

SEM

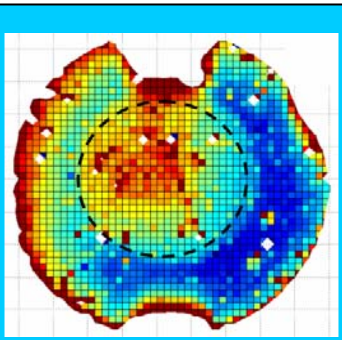
FTIR

…

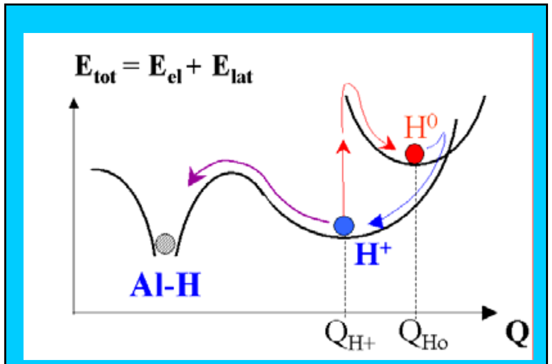
Traditional Material Characterization



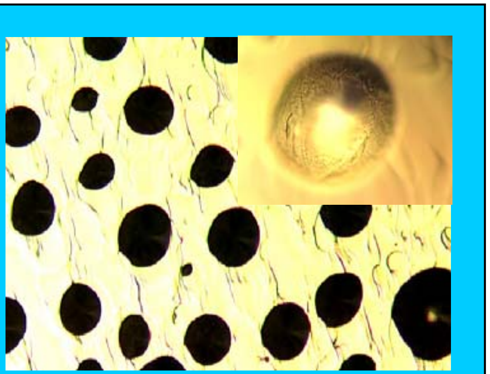
Epitaxial Process Simulation



Novel Non-Contact Material Characterization Techniques



Defects and Impurities. Defect Engineering in WBG Semiconductors



SiC for Nanotechnologies

Presentation Outline

1. Why SiC?
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3. **Advancements in SiC epitaxial growth**
4. Recombination Induced Defect Reactions involving hydrogen in SiC.

Lower-temperature epitaxial growth of 4H-SiC using CH_3Cl carbon gas precursor.

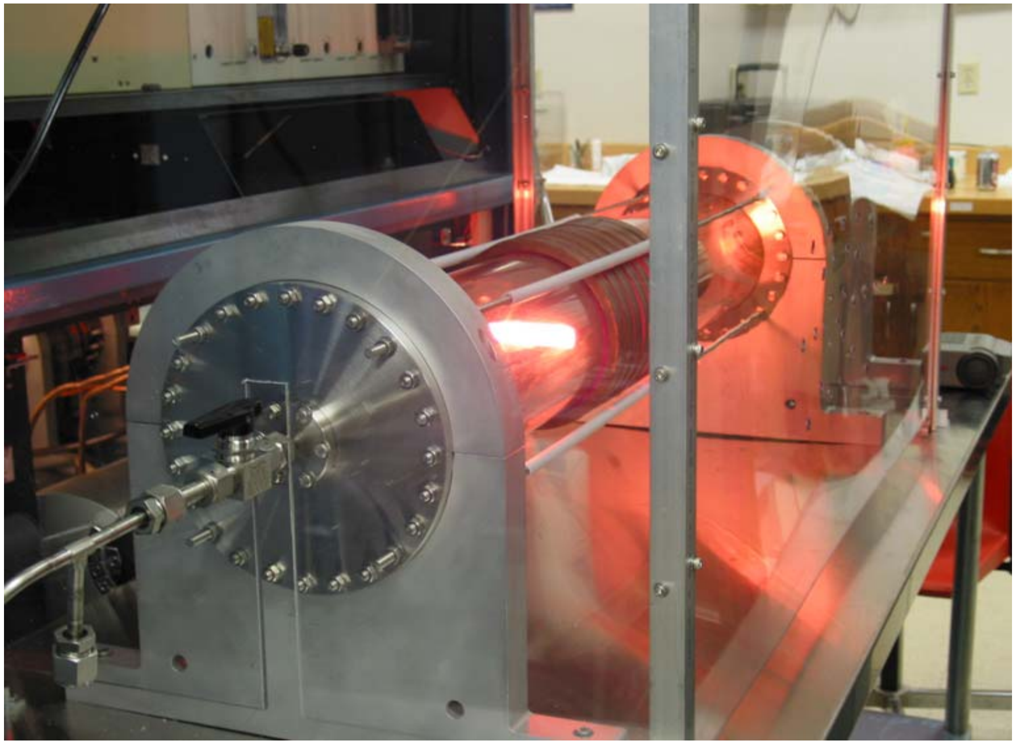
Huang-De Lin, Galyna Melnychuk, Yaroslav Koshka

[1] Mississippi State University, Box 9571,
Mississippi State, MS 39762, USA

The hot-wall CVD reactors.

Traditional Precursors:

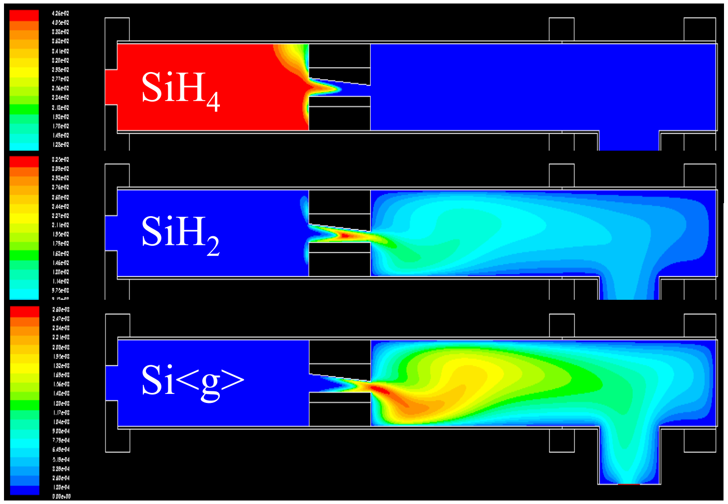
SiH_4 *and* C_3H_8



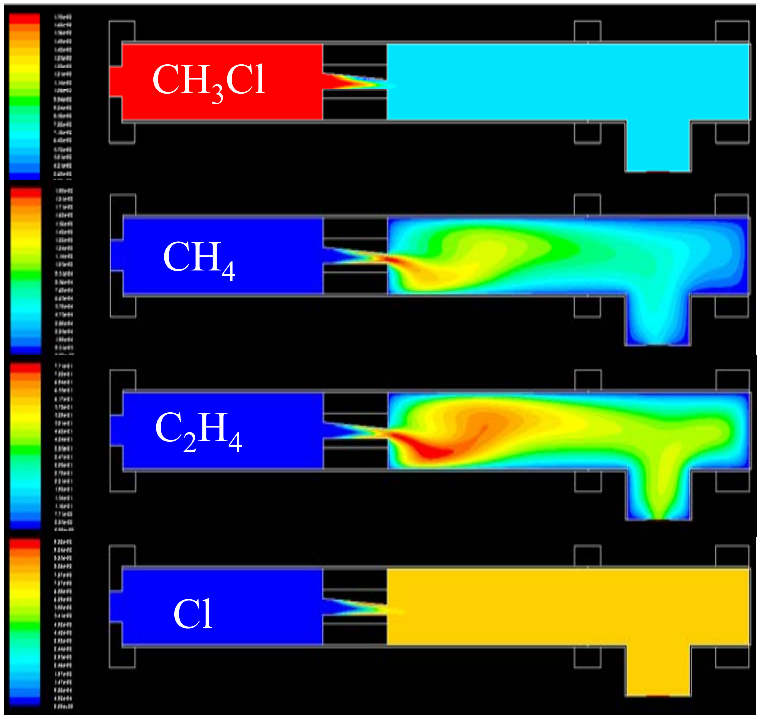
- Growth temperatures >1500^0C
- Lower temperatures => morphology degradation => polycrystalline

Simulated kinetics of chemical reactions of SiC epitaxial growth in the cross-section of the CVD reactor

Silane decomposition

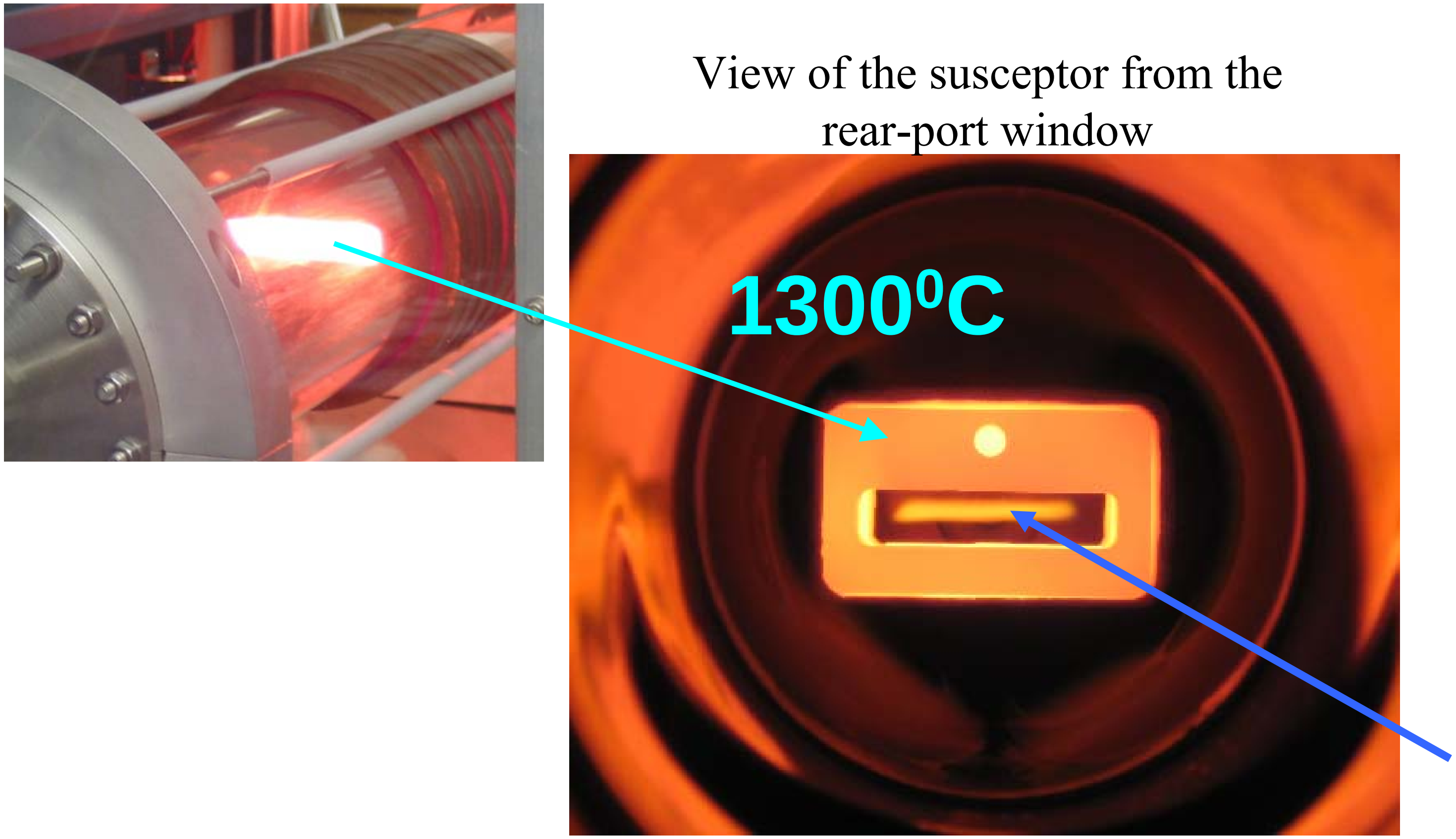


Chloromethane decomposition



Our new model – vapor-phase formation of Si droplets (clusters)

Growth at Lower Temperatures

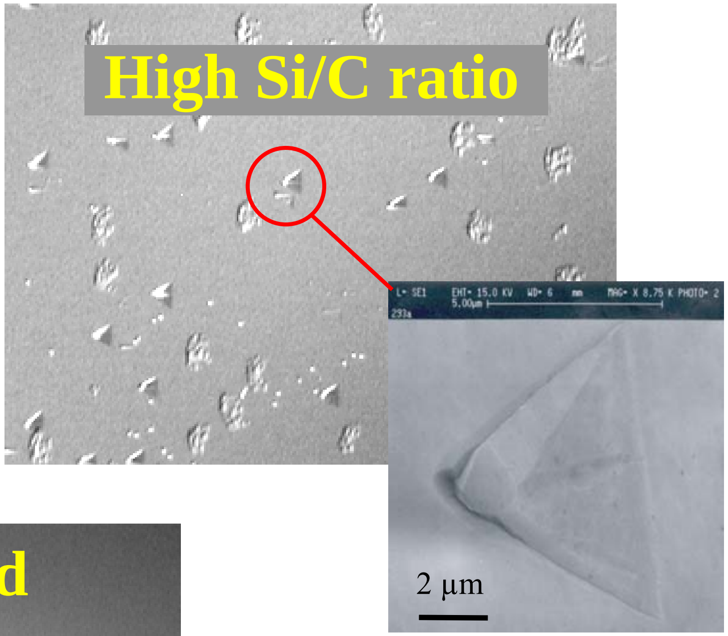


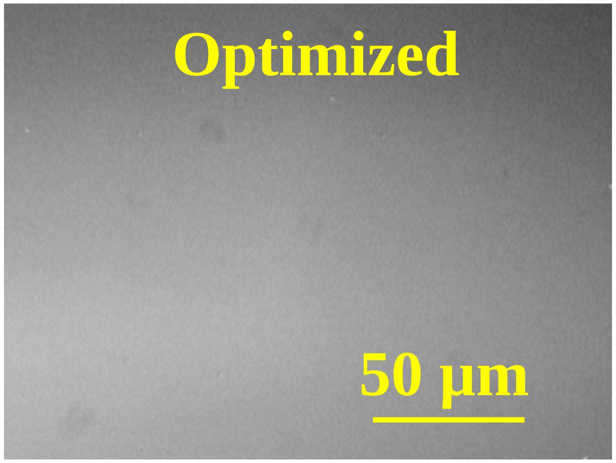
View of the susceptor from the rear-port window

Dense silicon-droplet cloud

- *Si vapor condensation (cloud) is detrimental for epi quality and growth rate.*

Surface morphology of the 1300^0C growth





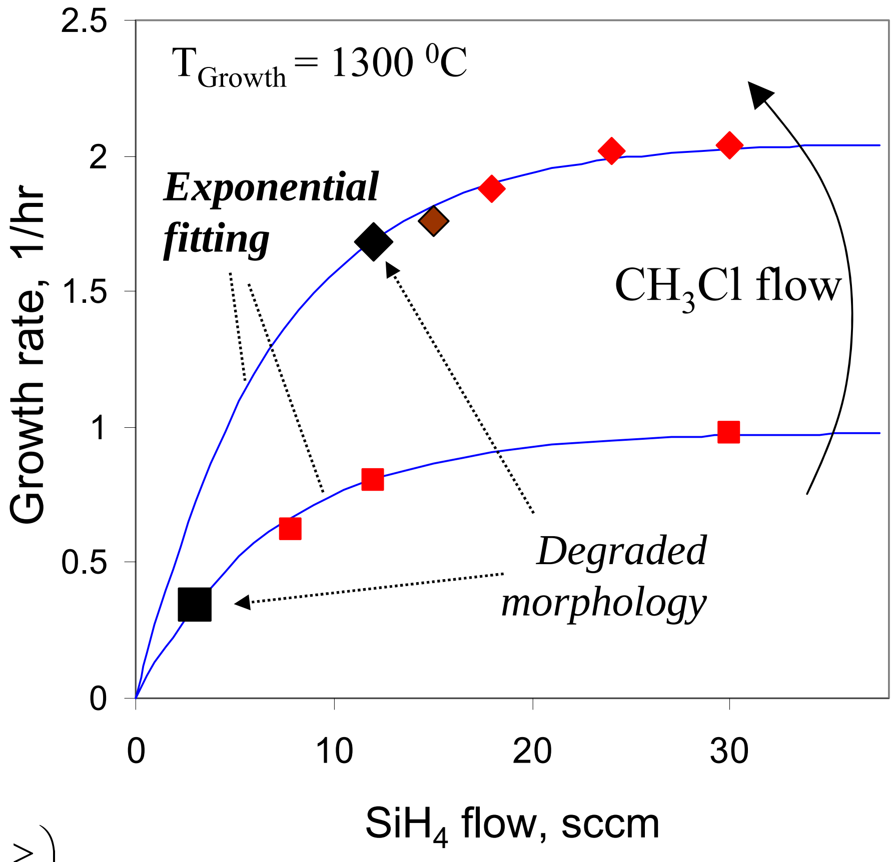
>2 µm/hr

J. of Crystal Growth

Patent Pending

Growth rate dependence on silane flow @1300^{0}C

The saturation of the growth rate at higher SiH_4 flows is due to silicon vapor condensation in clusters reducing the amount of Si available for epitaxial growth

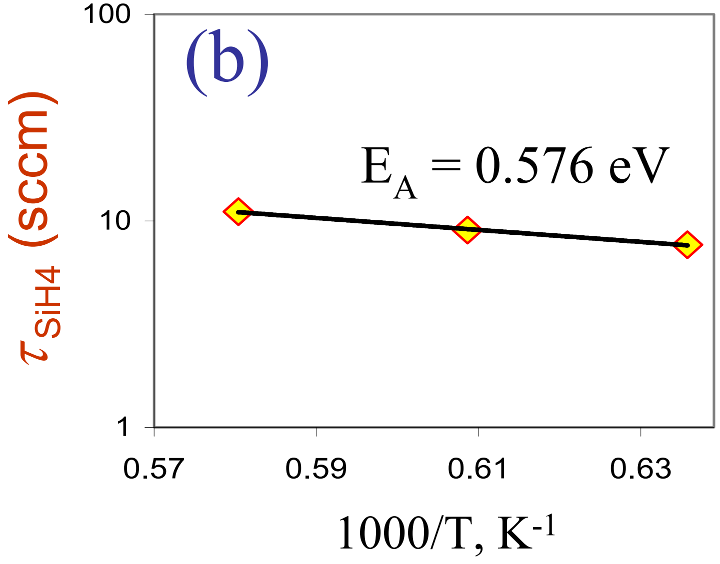


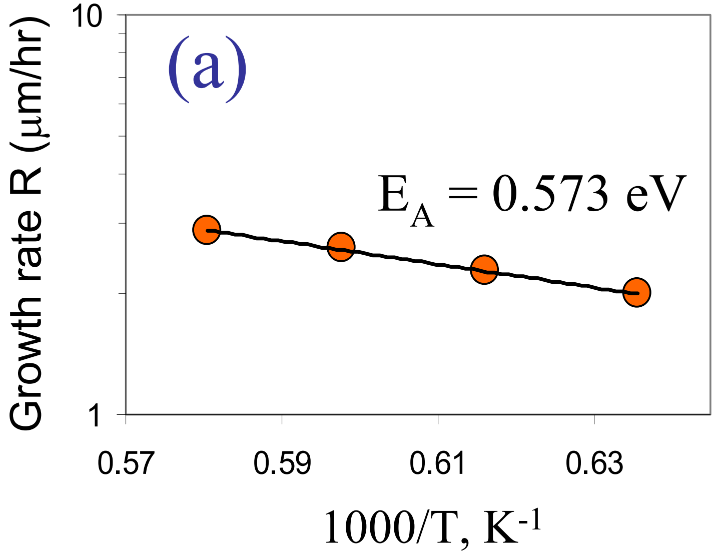
$$R(<SiH_4>) \propto 1-\exp\left(-\frac{<SiH_4>}{\tau_{SiH4}}\right)$$

J. of Crystal Growth

Arhenius temperature dependences:
(a) exponential rate coefficient of the SiH_4 flow dependence compared to
(b) the growth rate temperature dependence.

$$R(<SiH_4>) \propto 1 - \exp\left(-\frac{<SiH_4>}{\tau_{SiH4}(T)}\right)$$



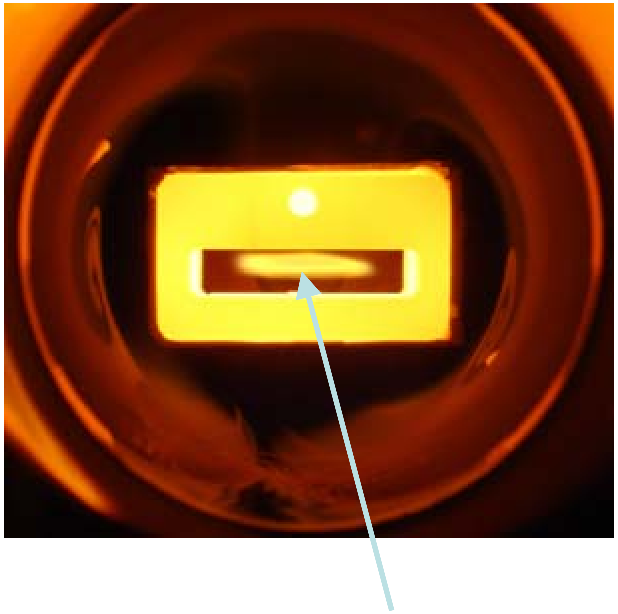


- The value of E_A is the same for R and τ_{SiH4} => the growth rate is determined by silicon vapor condensation.

HCl experiment:

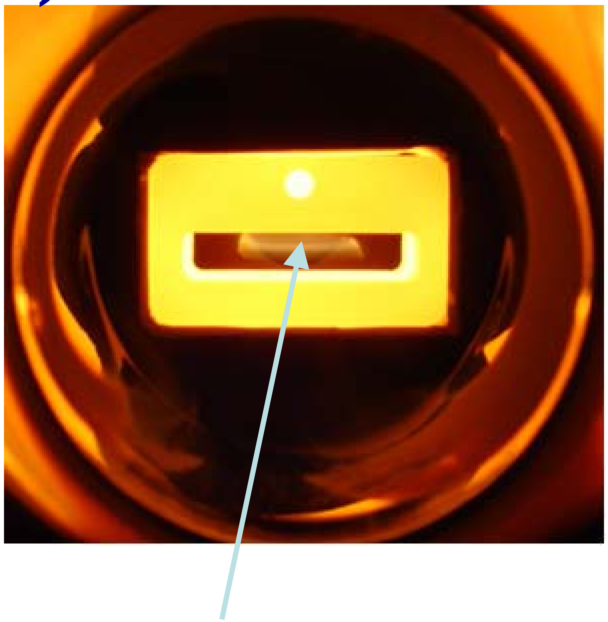
Rear view of the glowing susceptor during 1300^0C epitaxial growth

(a) No HCl



Dense cloud of Si clusters

(b) With HCl added



Strongly reduced cloud

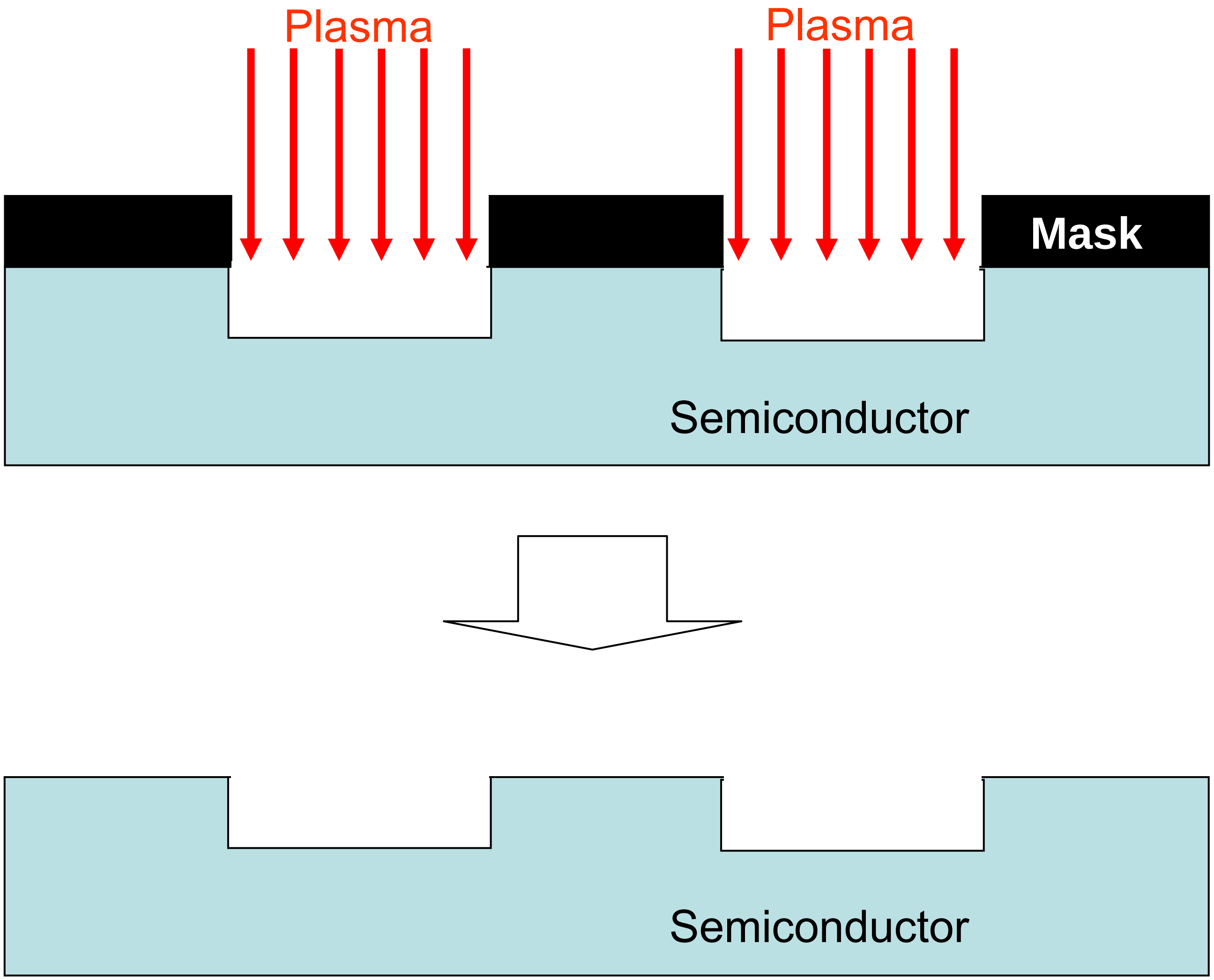
Selective epitaxial growth of 4H-SiC with SiO_2 mask.

Bharat Krishnan, Hrishikesh Das, Huang-De Lin,
Galyna Melnychuk, Yaroslav Koshka.

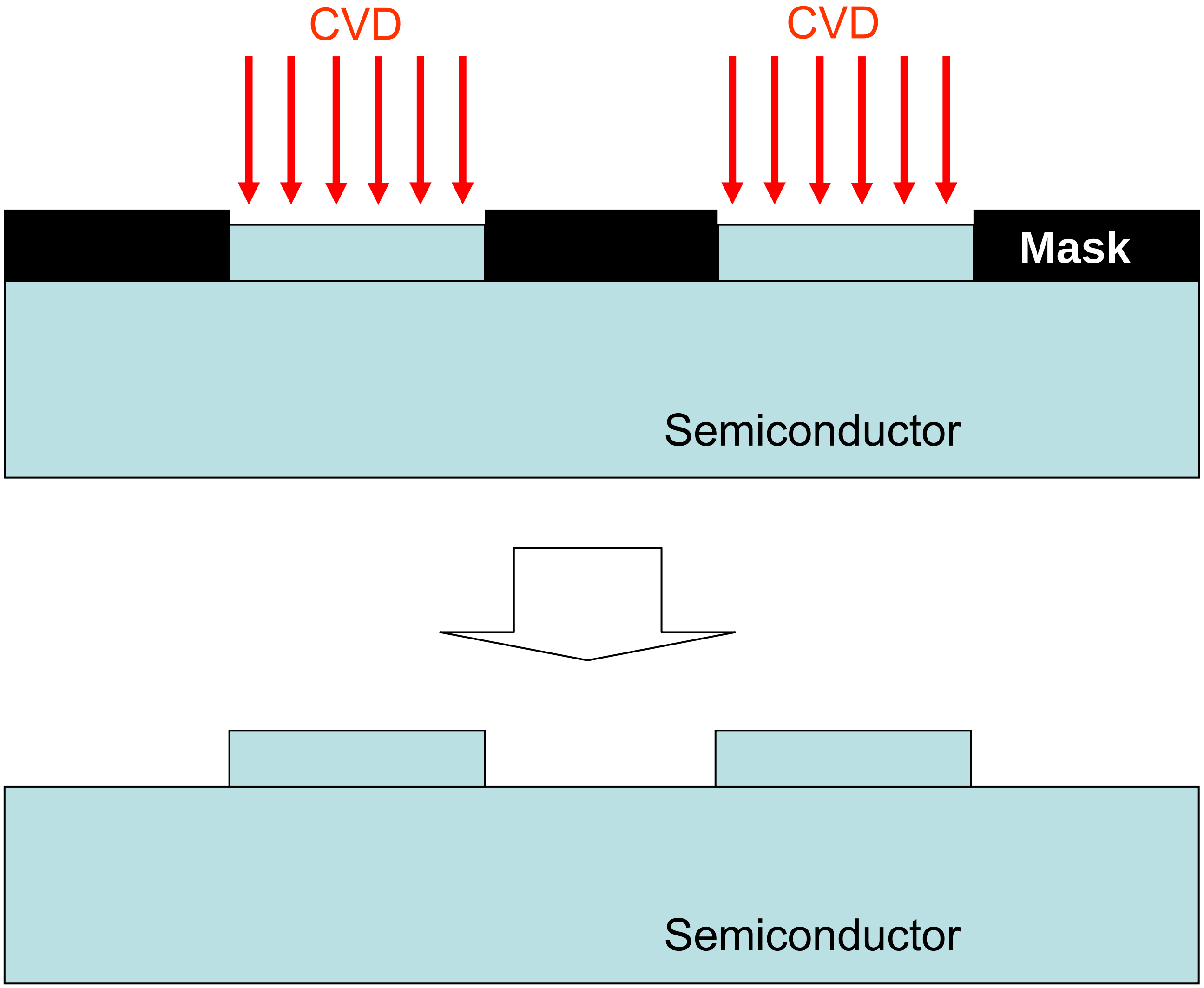
[1] Mississippi State University, Box 9571,
Mississippi State, MS 39762, USA

Patent Pending

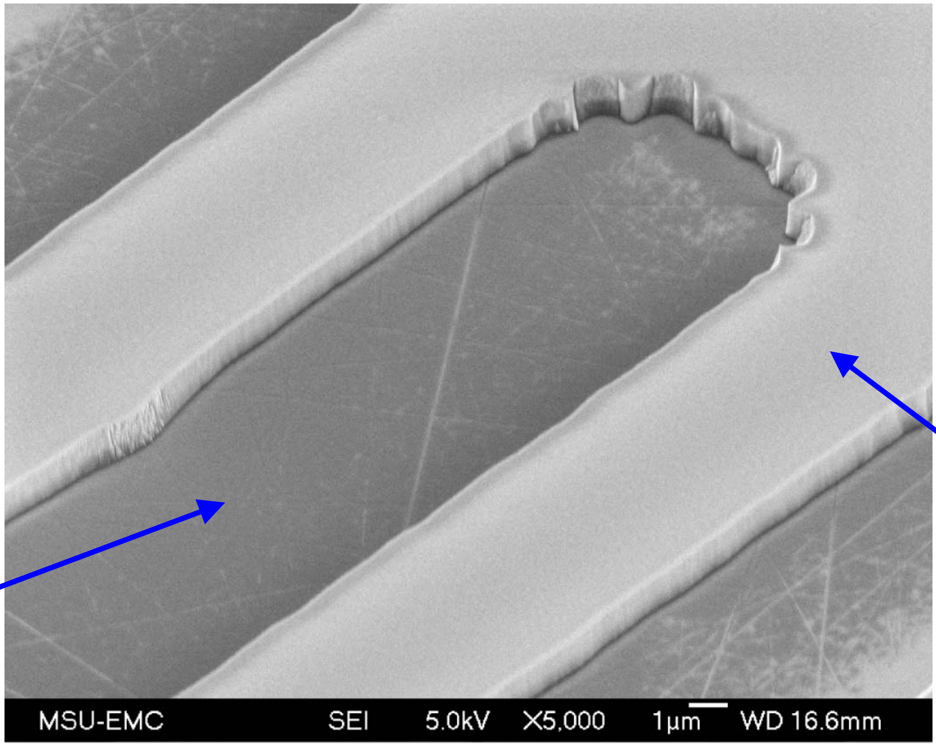
Pattern formation by Etching



Pattern formation by **Selective Epitaxial Growth**



SiO_2 mask for low-temperature selective epitaxial growth of 4H-SiC (LTSEG)



SiC substrate

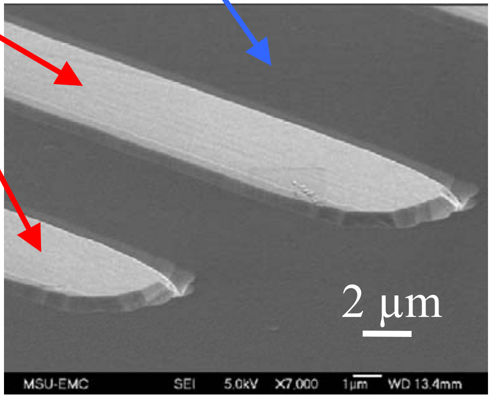
SiO_2 mask

- SiO_2 Severely degrade at regular growth temperatures (1500^0C)
- Survives at **1300^0C** of our novel low-temperature growth method

Low-temperature SEG at 1300^{0}C:

4H-SiC mesas

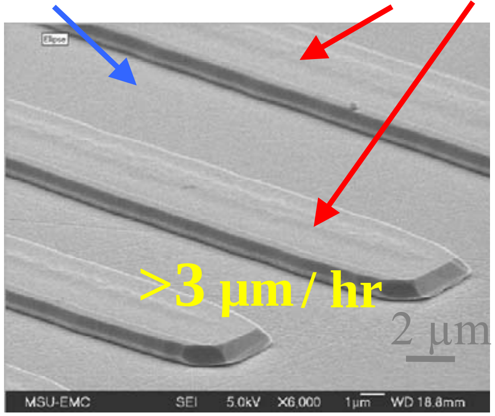
SiO_2 mask



(a) with SiO_2 mask

4H-SiC substrate

4H-SiC mesas



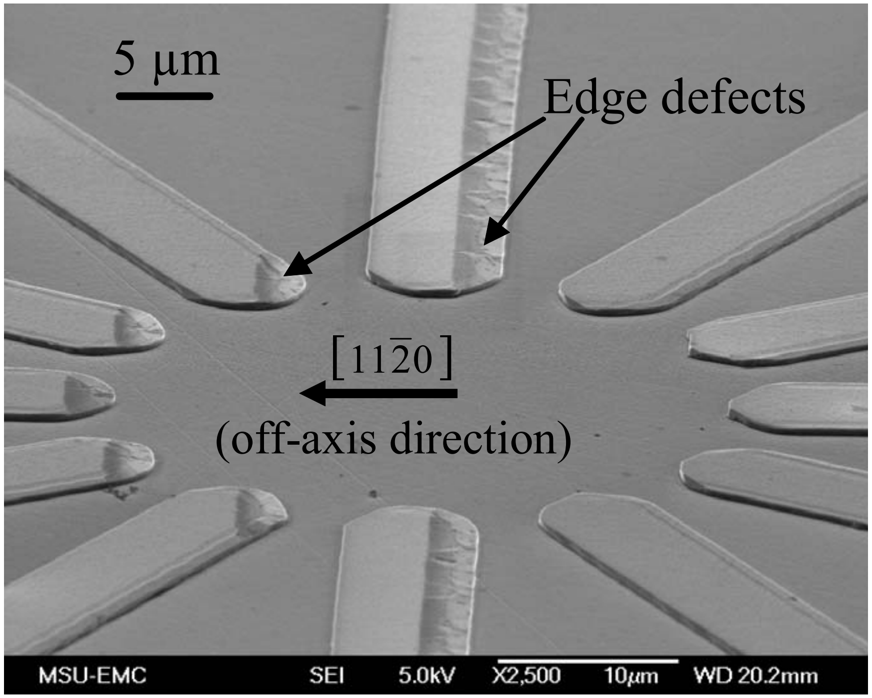
>3 µm / hr

(b) SiO_2 mask removed

Patent Pending

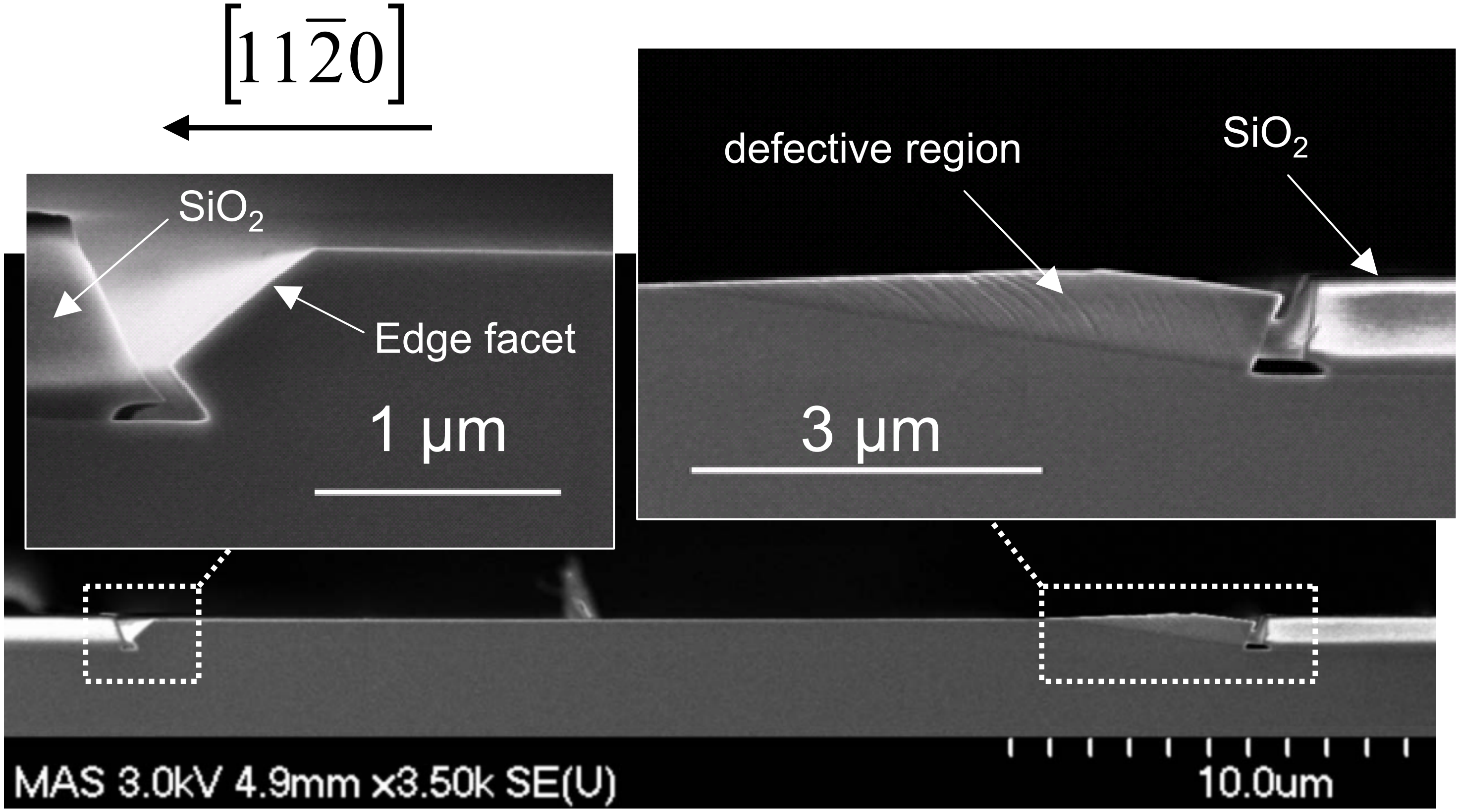
SEM image of the mesa-lines selectively grown in SiO_2 window at 1300^0C.

Lines oriented in different directions reveal the orientation-dependent defect generation.



Patent Pending

Cross-sectional SEM of 30-µm-wide mesa line selectively grown in SiO_2 window at 1300^0C.



Patent Pending

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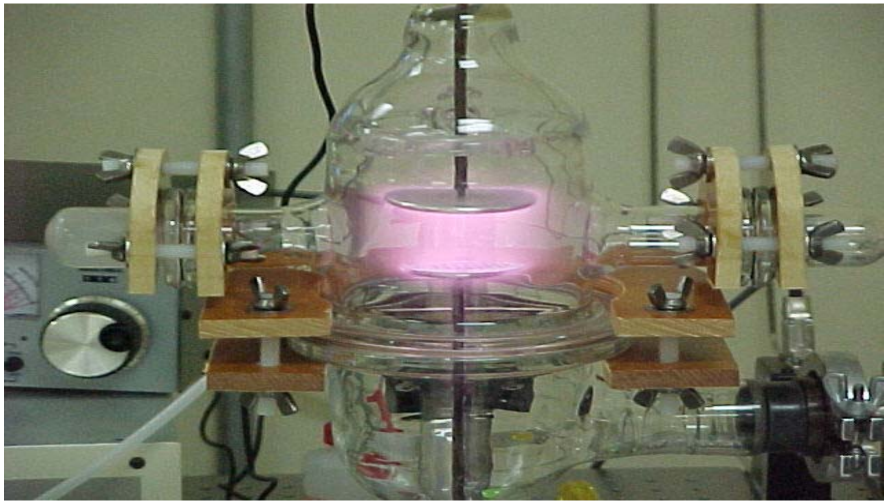
Plasma hydrogenation.

- Experimental Reactive Ion Etching (RIE) system → Hydrogen Plasma.

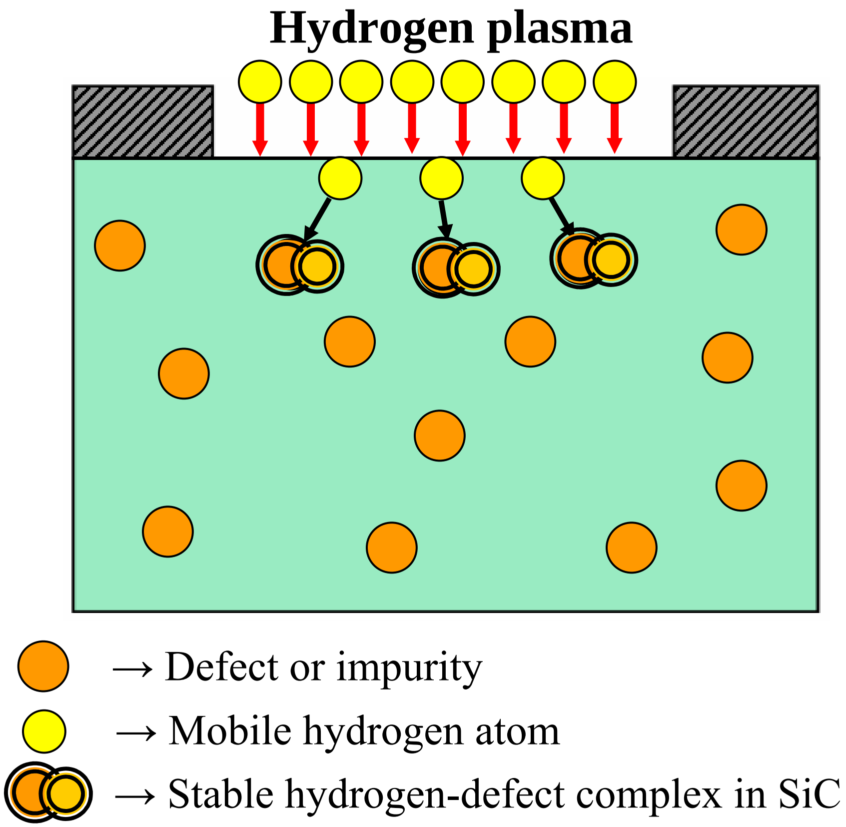


- Processing in new **Inductively Coupled Plasma** (ICP) system enabled further improvement of hydrogen incorporation in comparison to RIE hydrogenation.

SiC subjected to Plasma Hydrogenation.

- Incorporated hydrogen forms stable complexes with defects and impurities.
- Hydrogen concentration profiles repeat profiles of acceptor concentration.

[1] S. Janson, A. Hallén, M. K. Linnarsson, and B. G. Svensson, Phys. Rev. B 64, 195202 (2001)



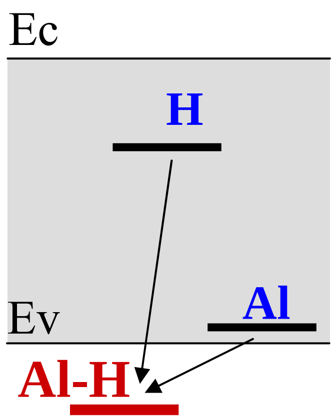
● → Defect or impurity

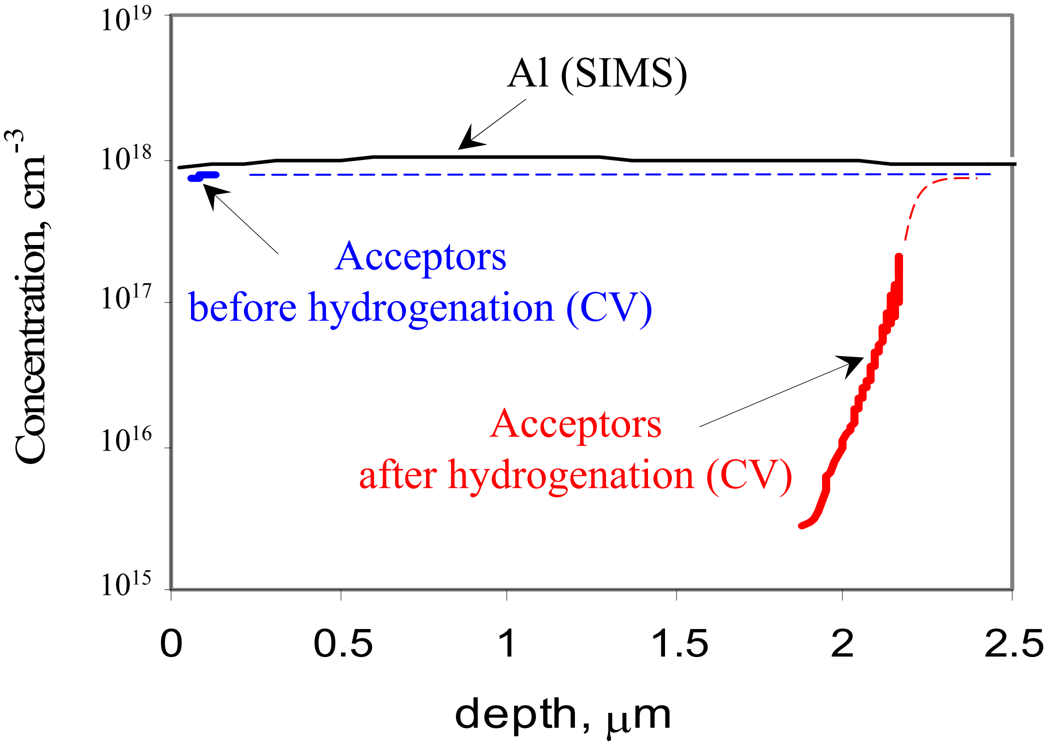
● → Mobile hydrogen atom

●● → Stable hydrogen-defect complex in SiC

Effect of plasma hydrogenation on the concentration of active acceptors (Al).

- Passivation of Al acceptors down to 10^{15}cm^{-3} and to the depth in access of 2 μm was achieved after 2 hrs of hydrogenation.



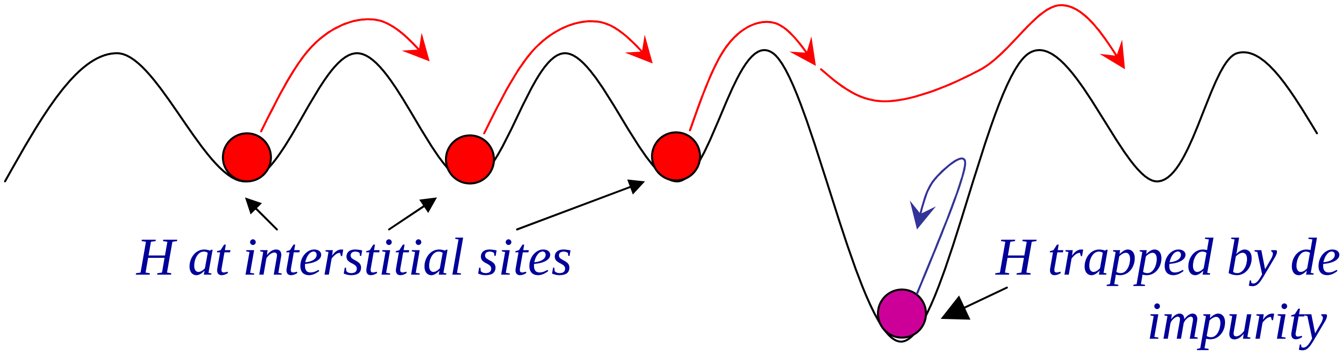


Simple Diffusion

$$\frac{\partial [H]}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial [H]}{\partial x}\right)$$

H – hydrogen concentration

Trap-Limited Diffusion



H at interstitial sites

H trapped by defect or impurity

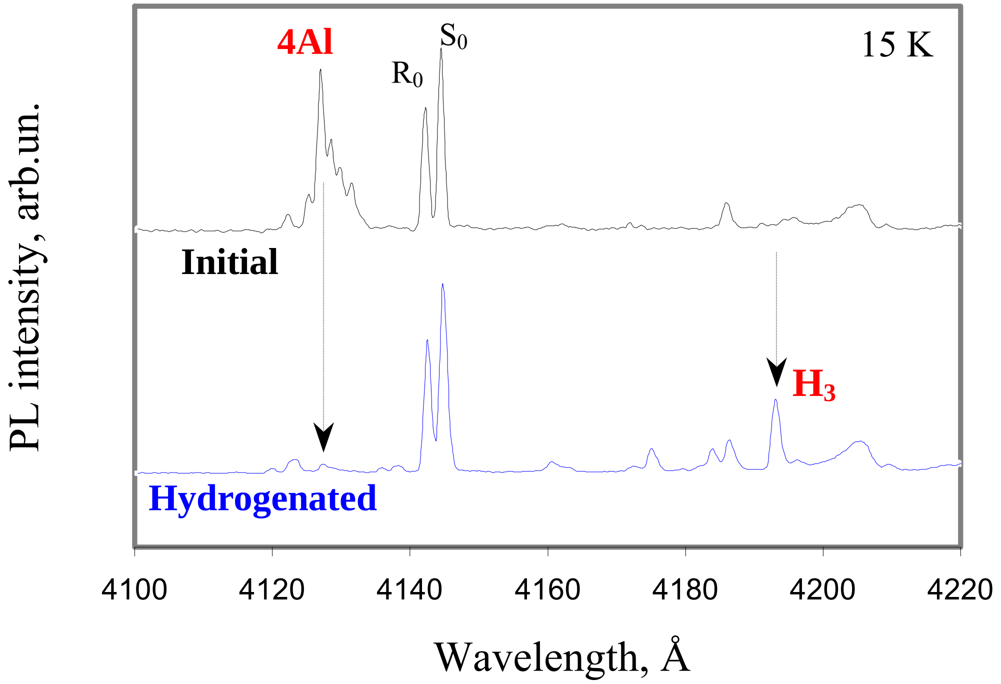
$$\frac{\partial [H]}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial [H]}{\partial x}\right) - \frac{\partial [HT]}{\partial t}$$

$$\frac{\partial [HT]}{\partial t} = K[H][T] - \nu[HT]$$

K – trapping constant.
ν – dissociation frequency

T – concentration of empty traps.
HT – concentration of traps filled with hydrogen.

PL spectra before and after plasma hydrogenation of epilayer moderately doped with Al.



- Efficient trapping of hydrogen by Al acceptors is confirmed by reduction of Al-BE PL;
- Al acceptors are not the only trapping centers for hydrogen. H-related PL lines indicate simultaneous formation of H complex with Si vacancy (V_{Si}-H).

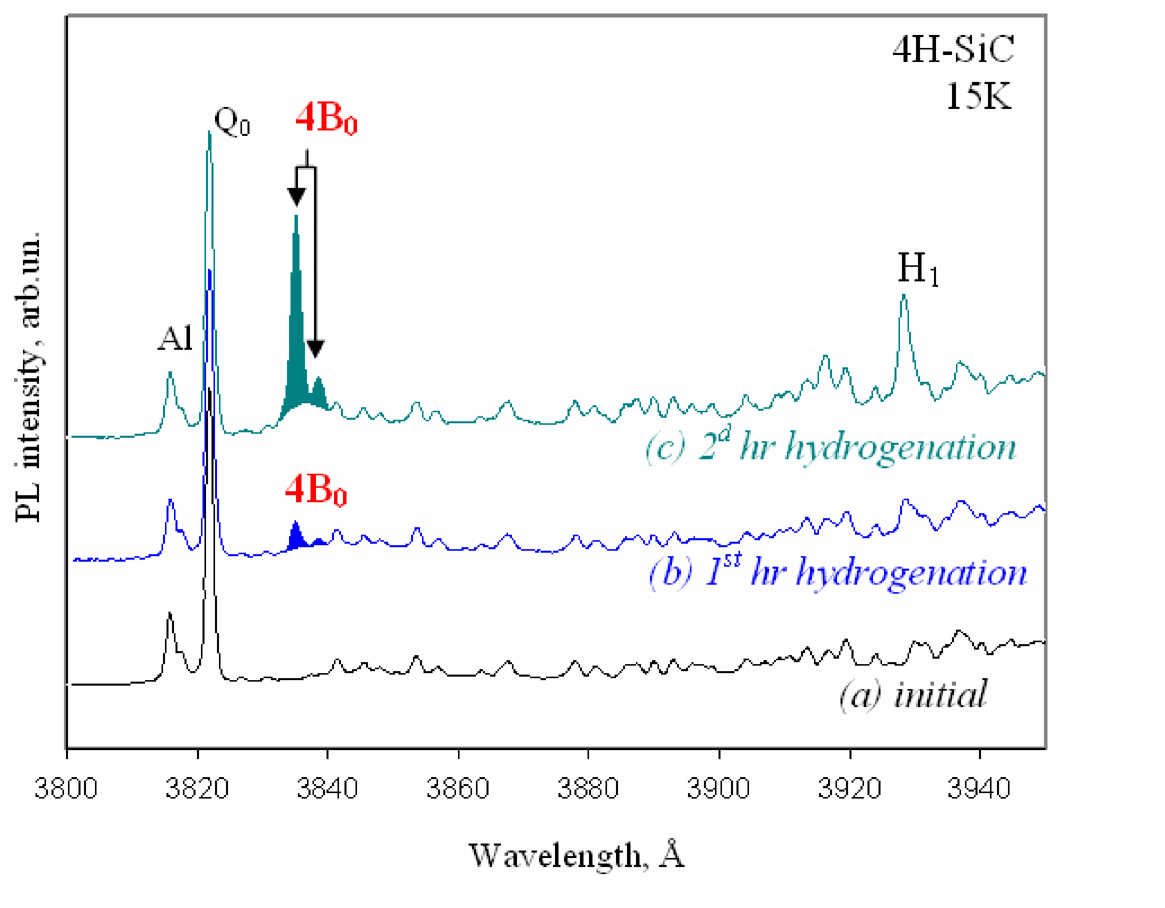
Y. Koshka, M. S. Mazzola, Appl. Phys. Lett, 79(6), 752 (2001)

PL spectra of B-doped 4H-SiC epilayer: affect of plasma hydrogenation:

- A **$4B_0$** peak previously associated with a bound exciton at the neutral boron is in fat related to a hydrogen-defect complex (possibly, B-H).

$p = 8\text{-}9 \times 10^{15}\ \mathrm{cm}^{-3}$

$t_{epi} = 5\ \mu m$



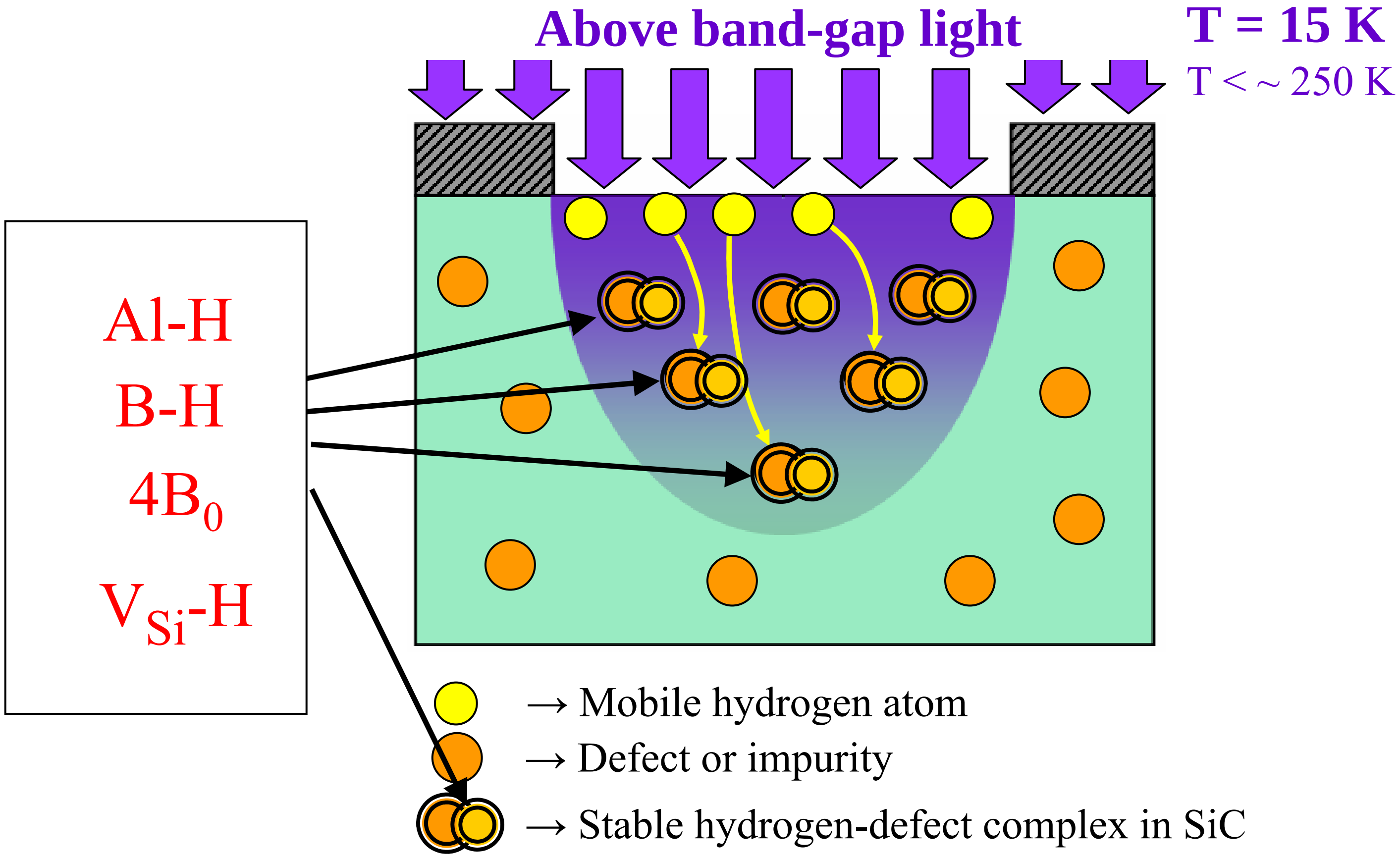
Y. Koshka, Appl. Phys. Lett., 82, 3260 (2003).

Phenomenon of Recombination-Induced Passivation (RIP)

Optically-stimulated passivation of defects with hydrogen.

Schematic illustration of Recombination-Induced Passivation.

- Certain amount of the incorporated hydrogen does not form stable complexes with defects (so called “free hydrogen”).
- Recombination-induced defect migration causes formation of various kinds of stable defect complexes.

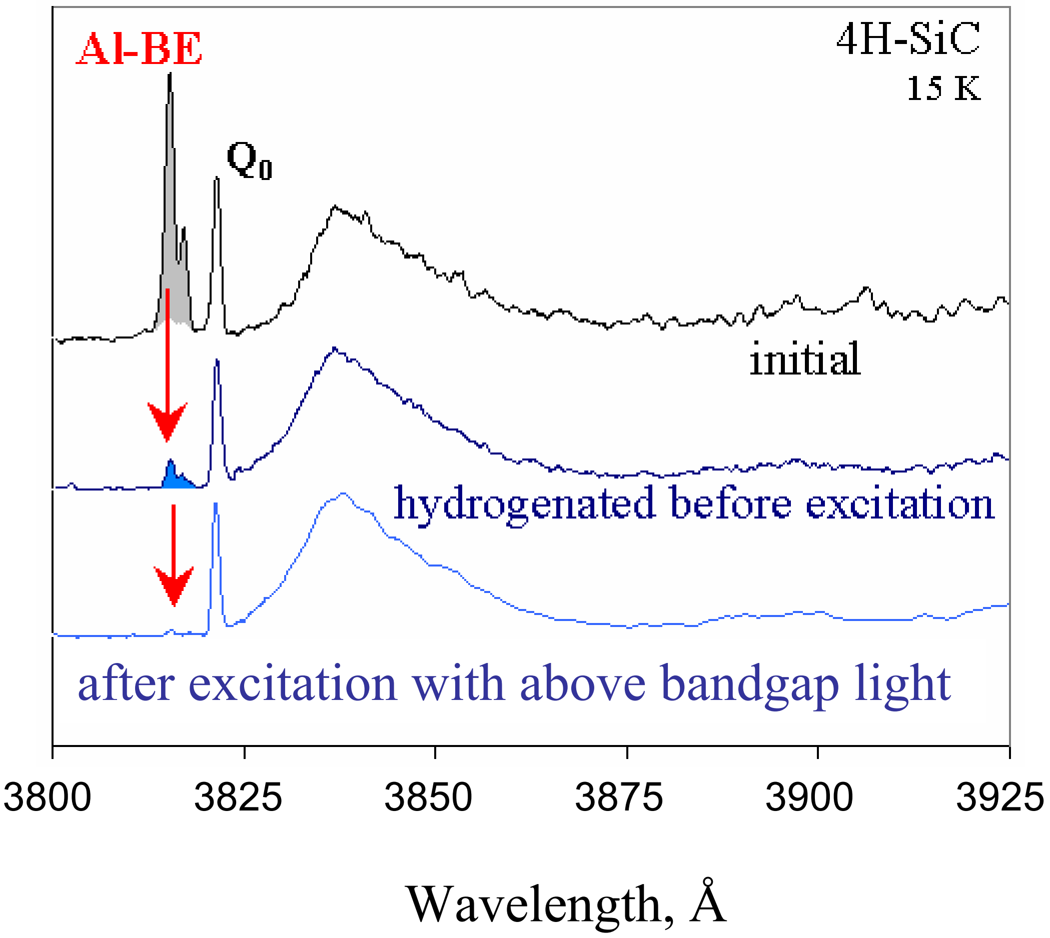


Photoluminescence spectra after Regular Hydrogenation and after Recombination Induced Passivation.

- Al-BE PL additionally quenches and disappears under optical excitation at low T in hydrogenated samples.

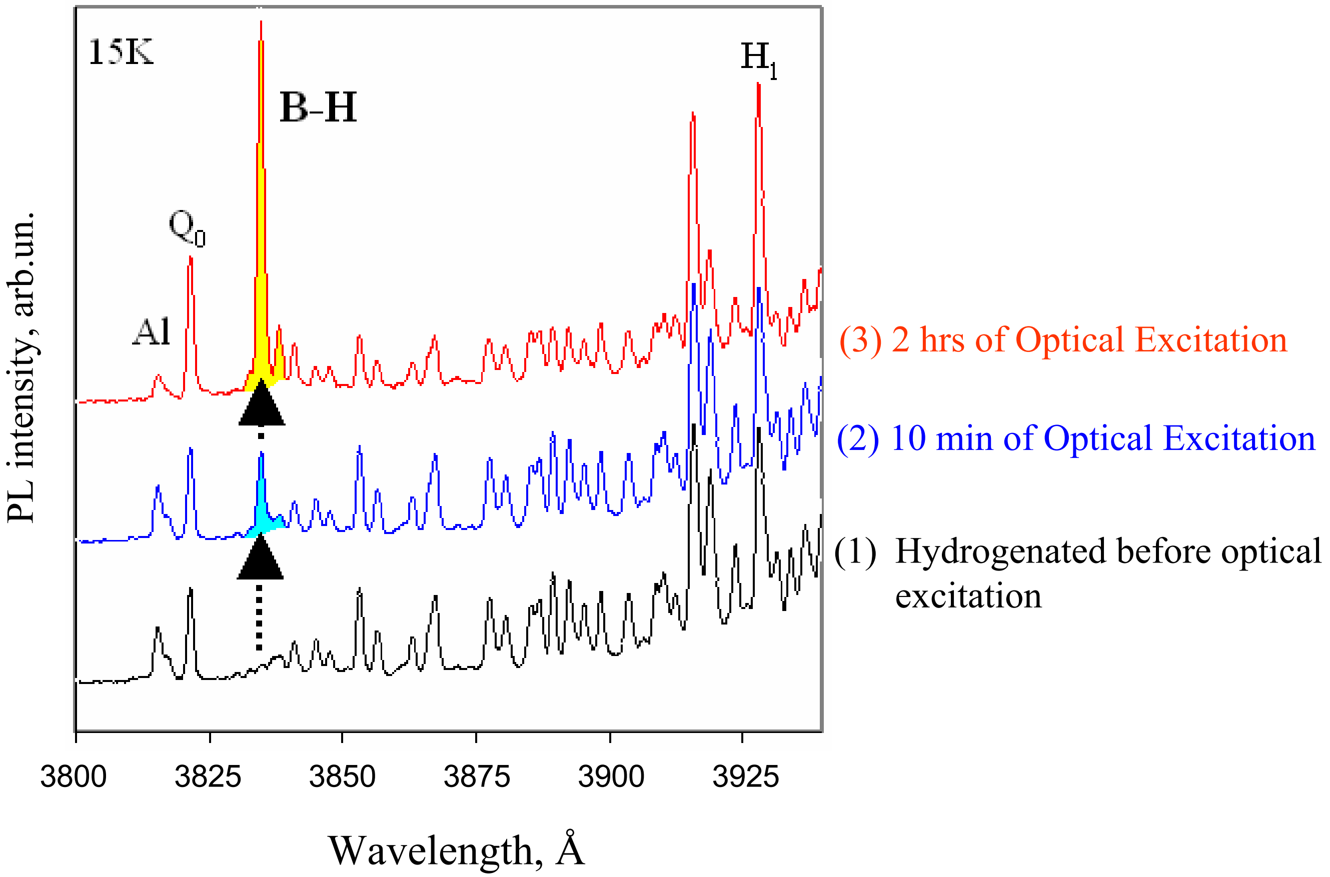
$p = 6\text{-}8 \times 10^{16}\ \mathrm{cm}^{-3}$

$t_{epi} = 2\ \mu\mathrm{m}$



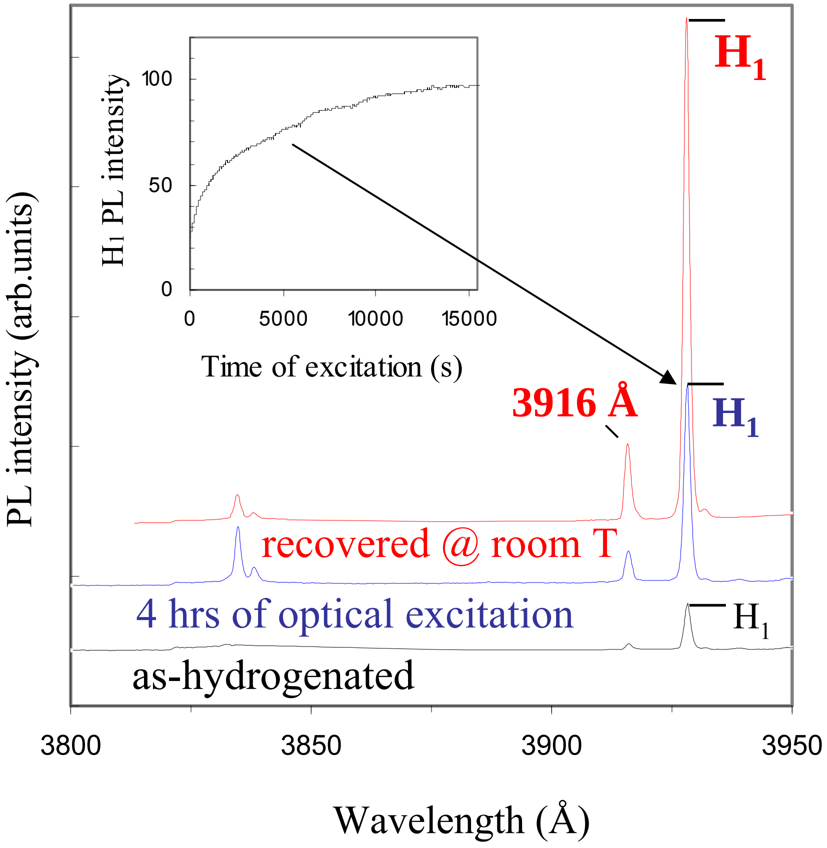
Changes in $4B_0$ PL caused by optical excitation at 15K

Recombination-Induced formation of defects responsible for $4B_0$ PL
(possibly Boron-Hydrogen complex).

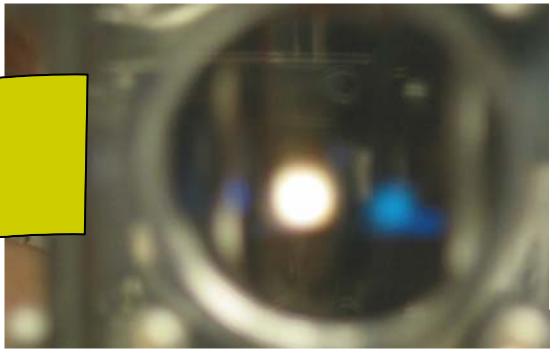


Optically induced changes of V_{Si}-H (H_1 line).

- The optically induced growth of H_1 can not be masked by the concurren metastable quenching.



Before Optical Excitation

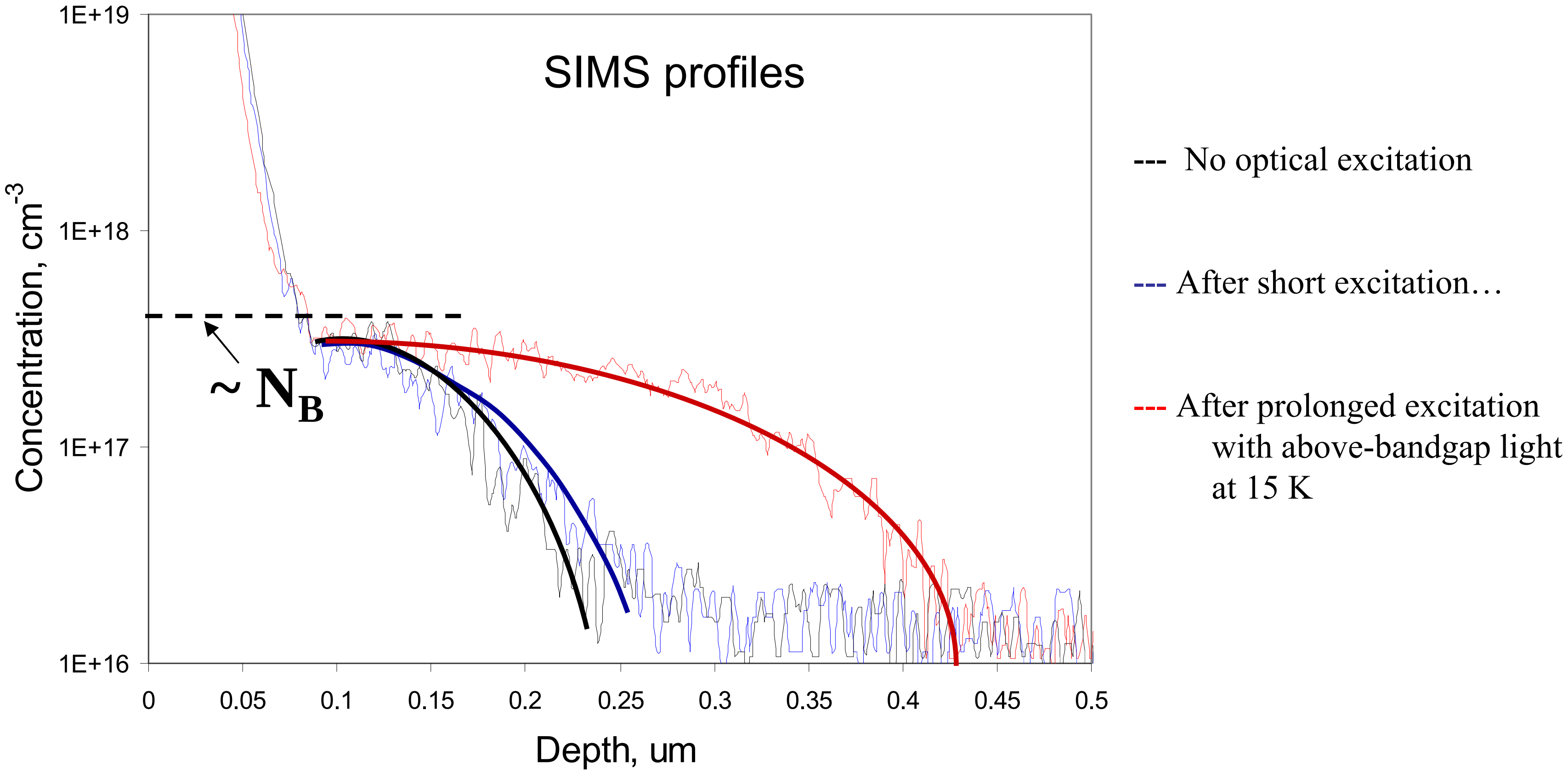


After Optical Excitation

Recombination-induced formation
of a strong radiative recombination channel
(V_{Si}-H emission)

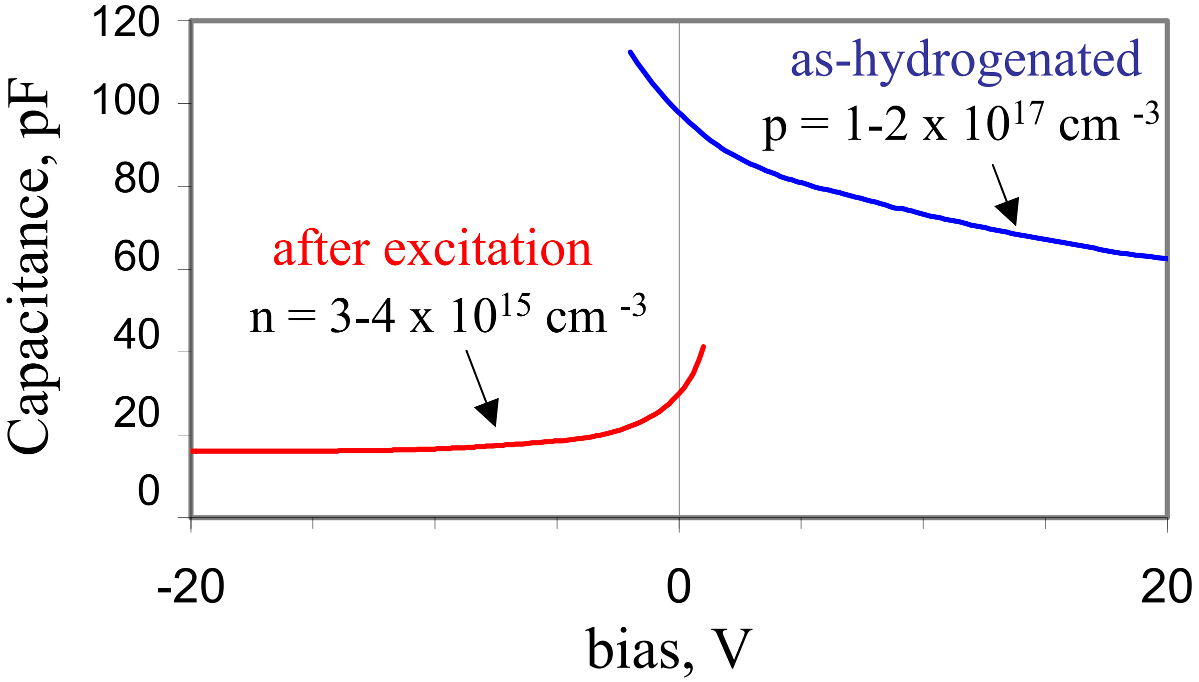
Deuterium concentration in plasma-deuterated B-doped SiC epitaxial layer.

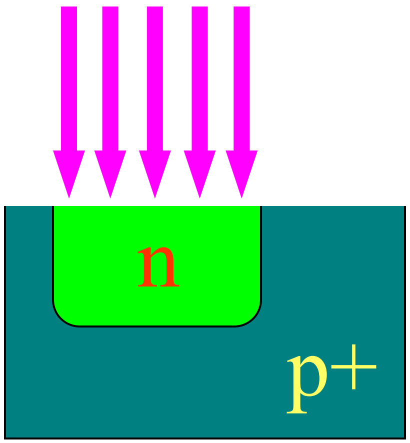
The spot subjected to an optical excitation at **15K** shows much deeper deuterium penetration => recombination-induced athermal migration.



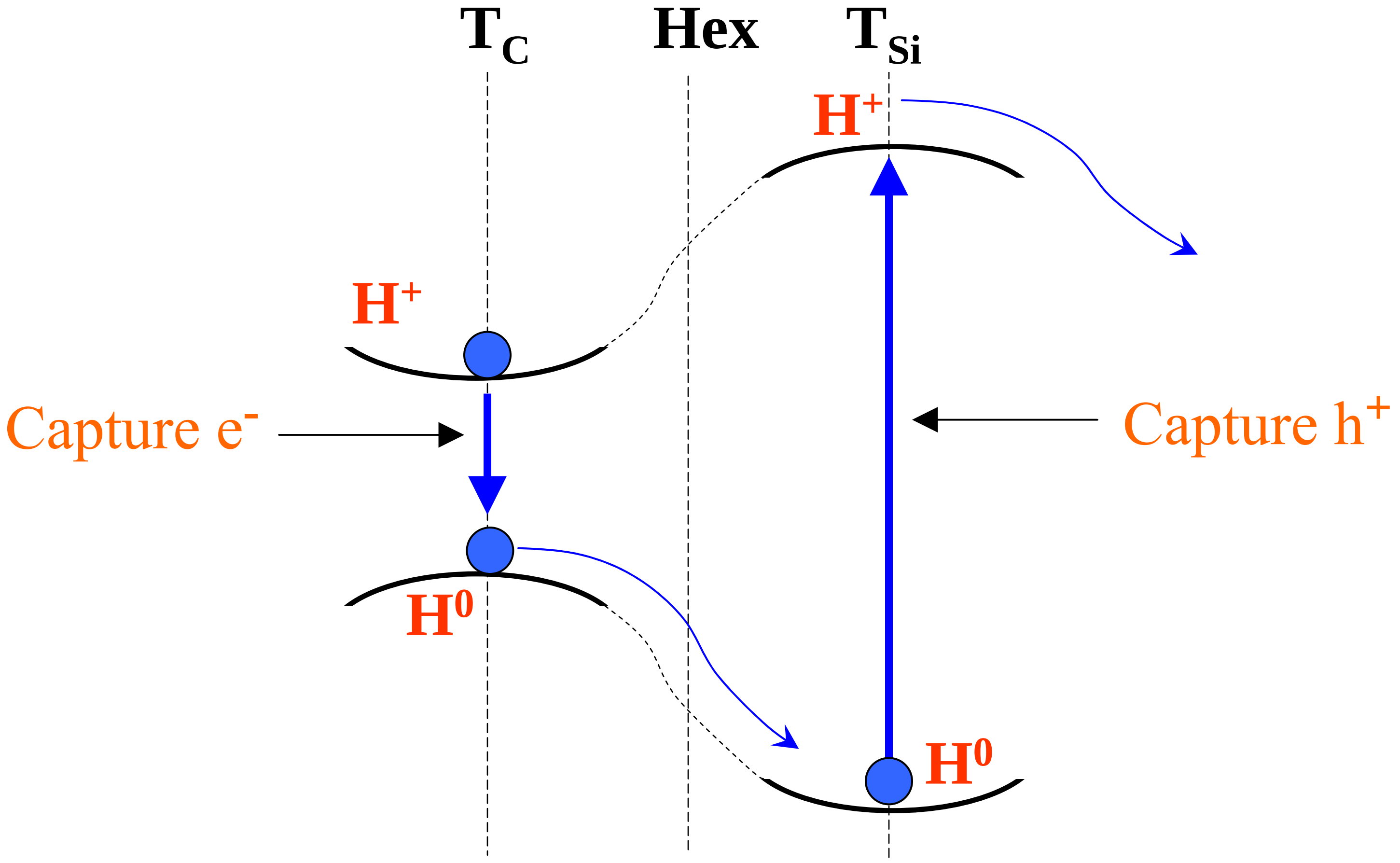
Inversion of the conductivity type under optical excitation in hydrogenated p-type epilayers:

❖ strong recombination-induced passivation of acceptors.





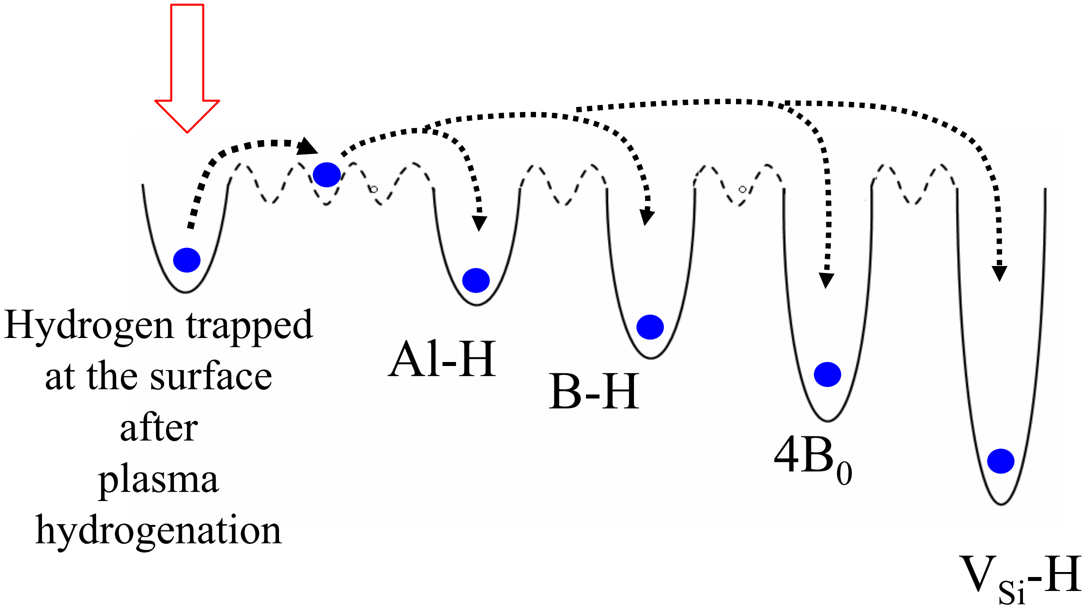
Hypothetical paths for H migration via Bourgoin-Corbett athermal migration mechanism.



Recombination-induced formation of Hydrogen-Defect Complexes:

Recombination energy => release of hydrogen from the trapping cites near the surface, athermal migration and trapping by more stable sites (e.g., Al and B acceptors, silicon vacancies, etc.)

RIP effect (Above-bandgap light at 4 - 250K)



Remaining questions …

- The exact path for H migration?
- The energy position of the hydrogen state responsible for the recombination-induced migration?
- Device applications?