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SMR.1135 - 10

THIRD WORKSHOP ON THIN FILMS PHYSICS AND TECHNOLOGY (8 - 24 MARCH 1999)
including
TOPICAL CONFERENCE ON MICROSTRUCTURE AND SURFACE MORPHOLOGY EVOLUTION IN THIN FILMS (24 - 26 MARCH 1999)

"H-mediation, surface segregation, ultra-high doping and their effects on Si and $Si_{1-x}Ge_x$ growth kinetics during GS-MBE and UHV-CVD"

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3rd ICTP/IUVSTA Workshop on Thin Film Physics
Trieste, Italy

H-Mediation, Surface Segregation, Ultra-High Doping and their Effects on Si and $Si_{1-x}Ge_x$ Growth Kinetics during GS-MBE and UHV-CVD

Joe Greene
University of Illinois

Monday, March 22, 8:30 to 10:30

Outline:

1. ALE Si
   a. Mechanisms
   b. Modeling
2. GS-MBE/UHV-CVD Si
   a. Mechanisms
   b. Modeling
3. B doping
   a. Incorporation mechanism
   b. Electronic properties
4. Ultra-high B doping
   a. Incorporation
   b. Effect on R_{Si}
   c. Modeling
   d. Electronic properties
5. GS-MBE/UHV-CVD $Si_{1-x}Ge_x$
   a. Mechanism
   b. Modeling
   c. B doping and electronic properties

Atomic-level Control during Film Growth under Highly Kinetically Constrained Conditions

* $Si_{1-x}Ge_x$ atomic-layer epitaxy (ALE)
- Low-temperature growth
- δ-doping

* Effects of H coverage during GS-MBE/UHV-CVD
- Ultra-high doping vs film growth kinetics
- Minimize Ge segregation during $Si_{1-x}Ge_x$ growth

* Fundamental limits of epitaxy
- $T_{epi} \rightarrow t_{epi}$
- Use of hyperthermal beams
- Metastable phases ($Ge_{1-x}Sn_x$, $Ti_{1-x}Al_xN$, ...)

* Evolution of surface morphology
- Kinetic roughening
- Strain-induced roughening/smoothening

* Evolution of microstructure and texture
- Hyperthermal beams
- Texture inheritance

Atomic-Layer Epitaxy (ALE)

ALE is a cyclic vapor-phase epitaxial film growth technique which incorporates *self-limiting* kinetic processes which result in the deposition of θ ML per growth cycle where $\theta \leq 1$ ML.

$$\Rightarrow R_{cycle} = \theta \text{ (ML/cycle)}$$

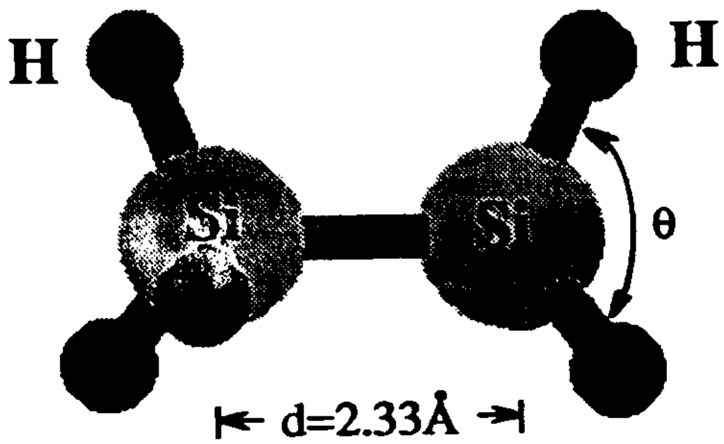
Advantages:

- $R \neq f(T_s, P_{gas})$; wide process windows
- $\therefore$ overall $E_a = 0$
- $\therefore$ low T_s possible
- Excellent control over film thickness:
  $t = R_{cycle}(\#cycles)$
- Selective area deposition
- δ-doping
- QW heterostructures
-
-

Precursor for Si ALE: Si_2H_6

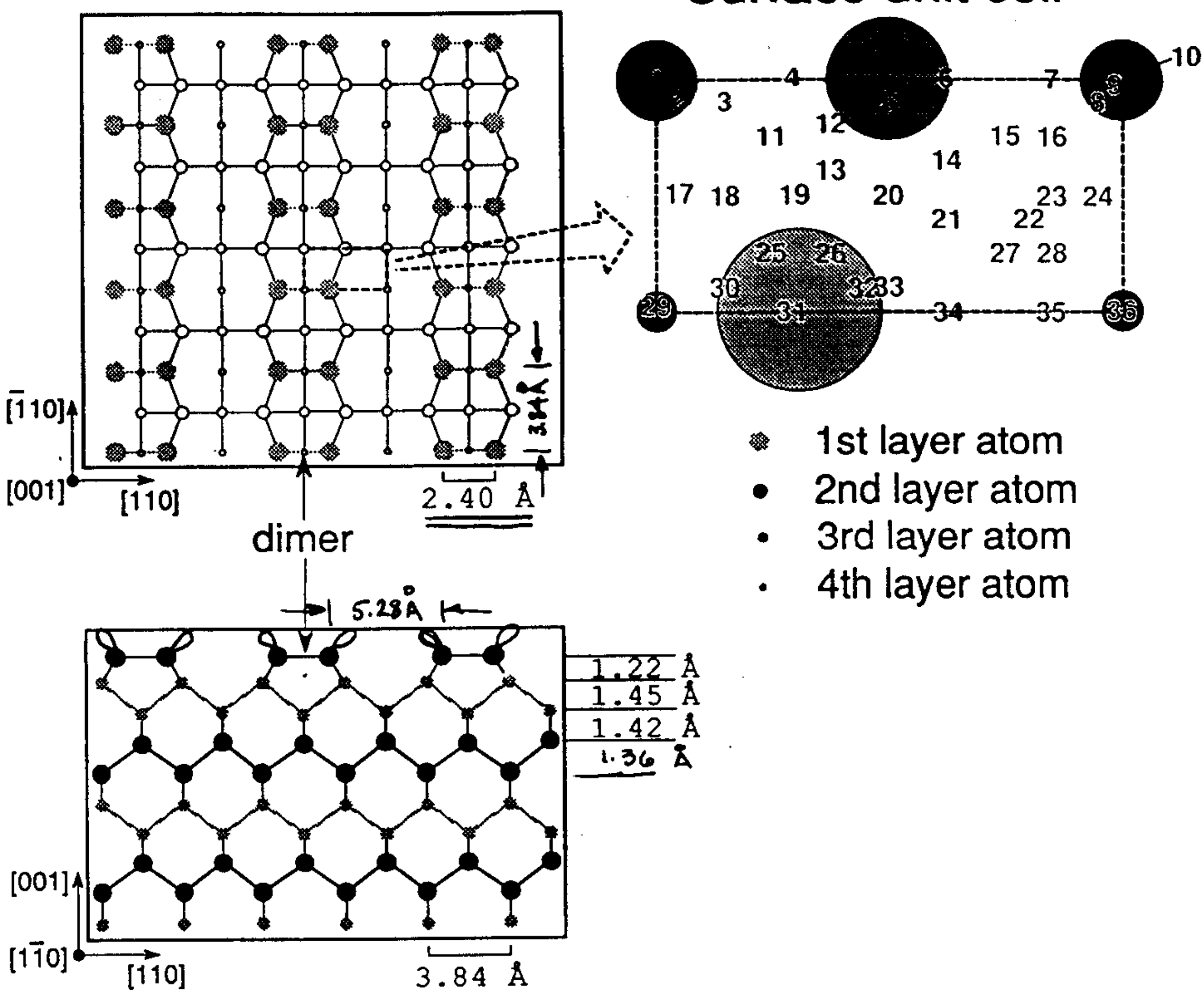
- High sticking probability on Si & Ge
  $\sigma(Si_2H_6) > 10^4 \times \sigma(SiH_4)$

- Gas phase dimer ≃ Si(001)2x1

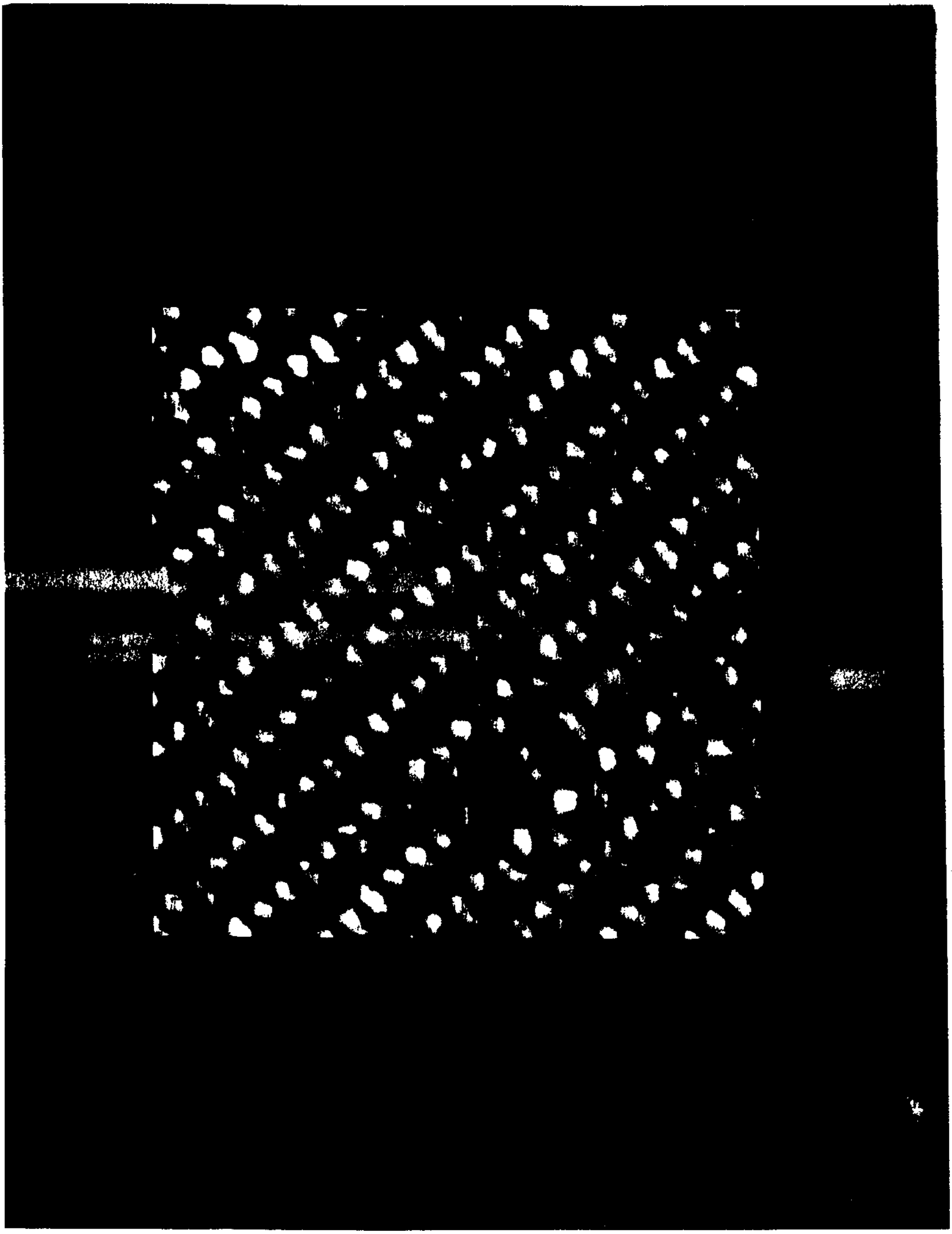


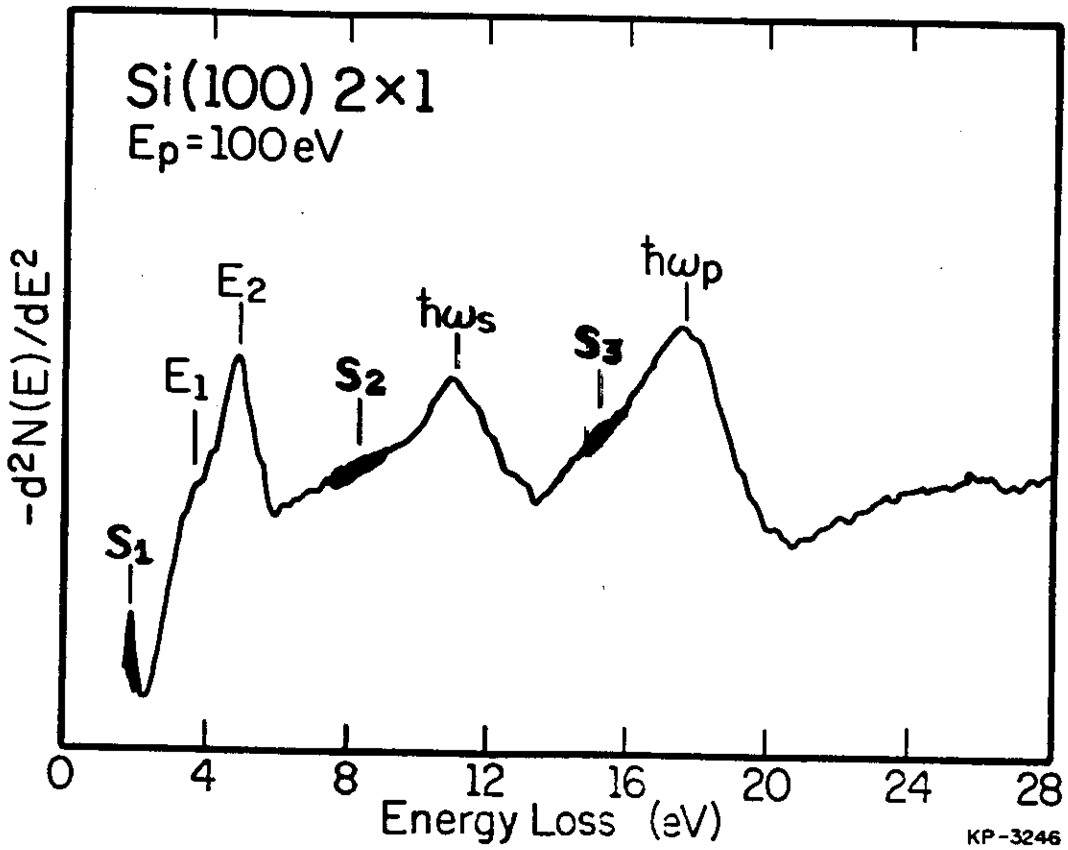
- E_b(Si-Si) = 3.3 eV
- E_b(Si-H) = 3.8 eV
- d(Si-Si) = 2.33 Å
- d(Si-H) = 1.49 Å
- θ(Si-Si-H) = 110.3°

Surface unit cell

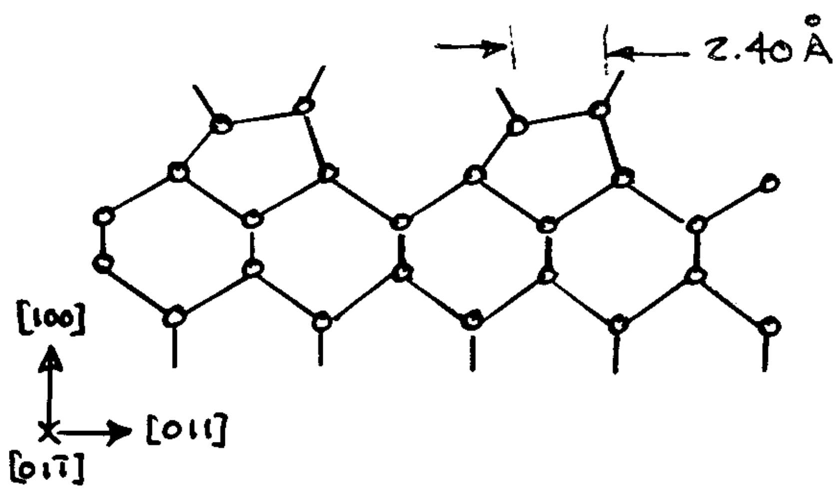


M. Kitabutake and J.E. Greene, J. Appl. Phys. 73, 3183 ('93).

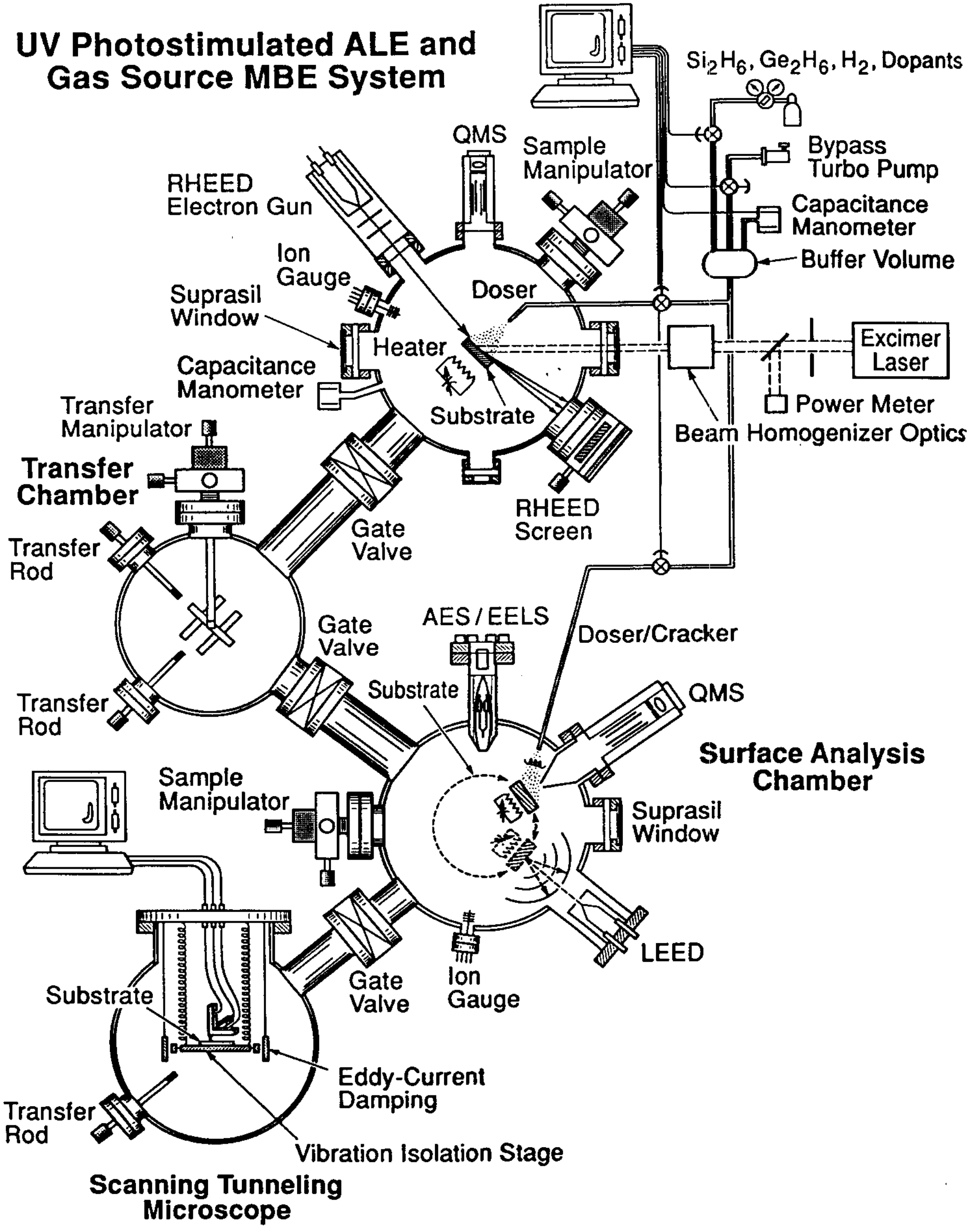




S_1 = surface dangling bond state
S_2, S_3 = backbond states

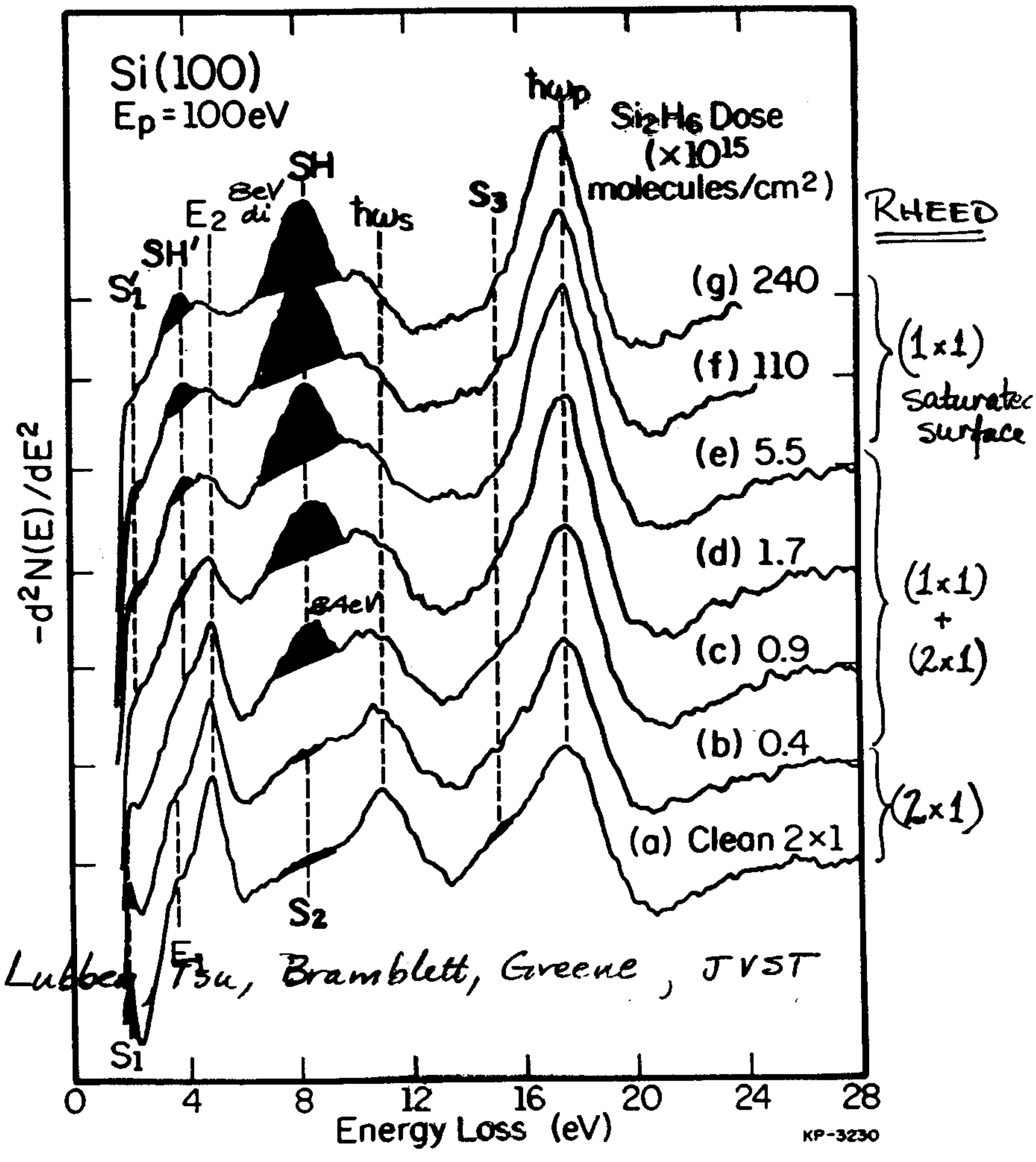


UV Photostimulated ALE and Gas Source MBE System



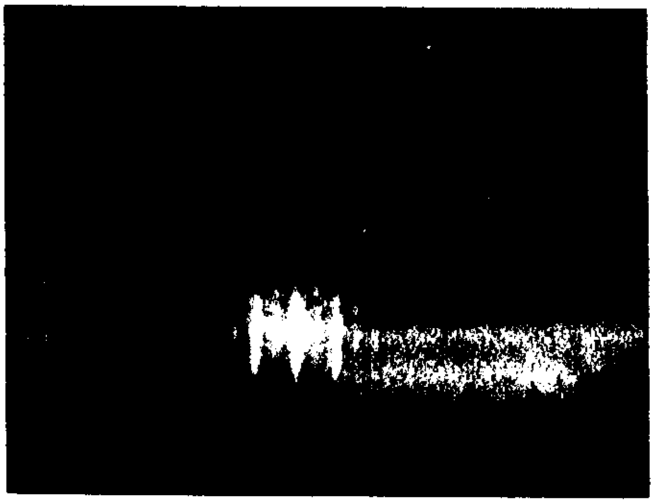
KP-3506
ABELSON

$T_s = 300\ K$

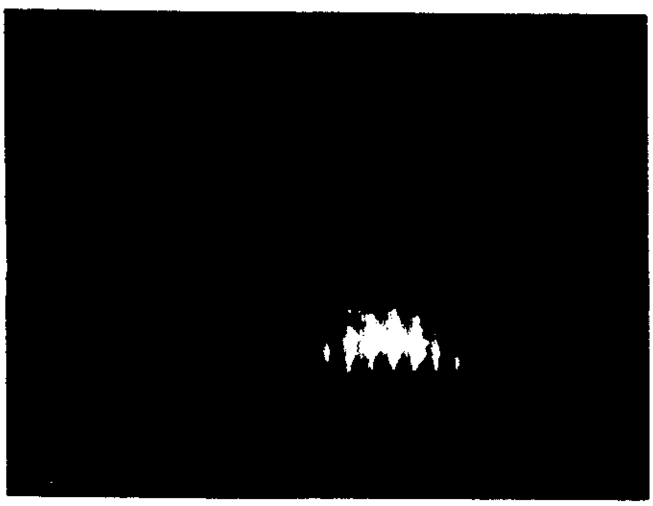


Lubben, Tsu, Bramblett, Greene, JVST

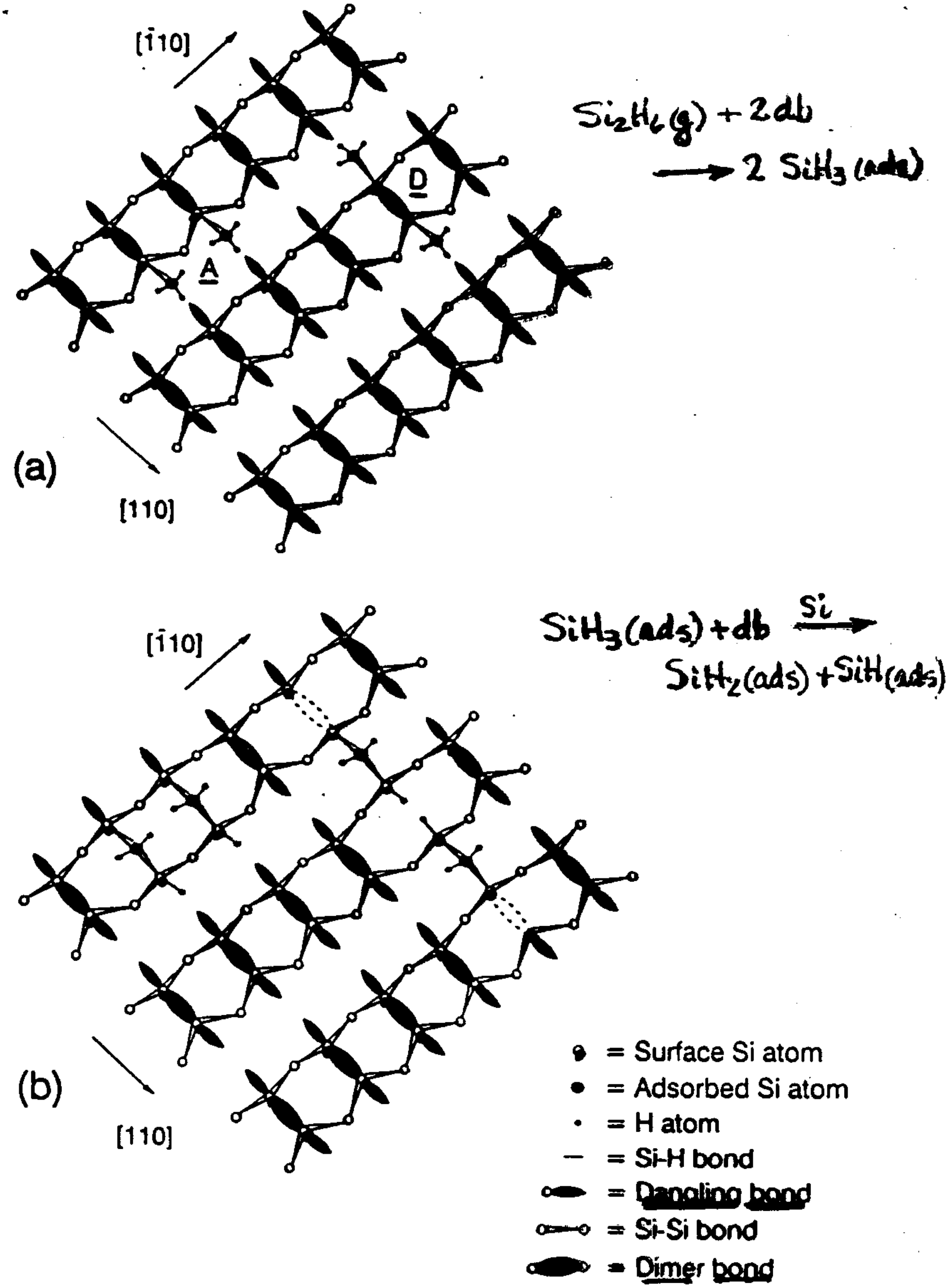
1×1



2×1
+
1×1



2×1



7. Schematic illustration of the Si(001) surface after (a) dissociative chemisorption of Si_2H_6 onto a single dimer (D) and onto adjacent dimers (A), and (b) dissociation of the adsorbed SiH_3 radicals to form SiH_2 and H.

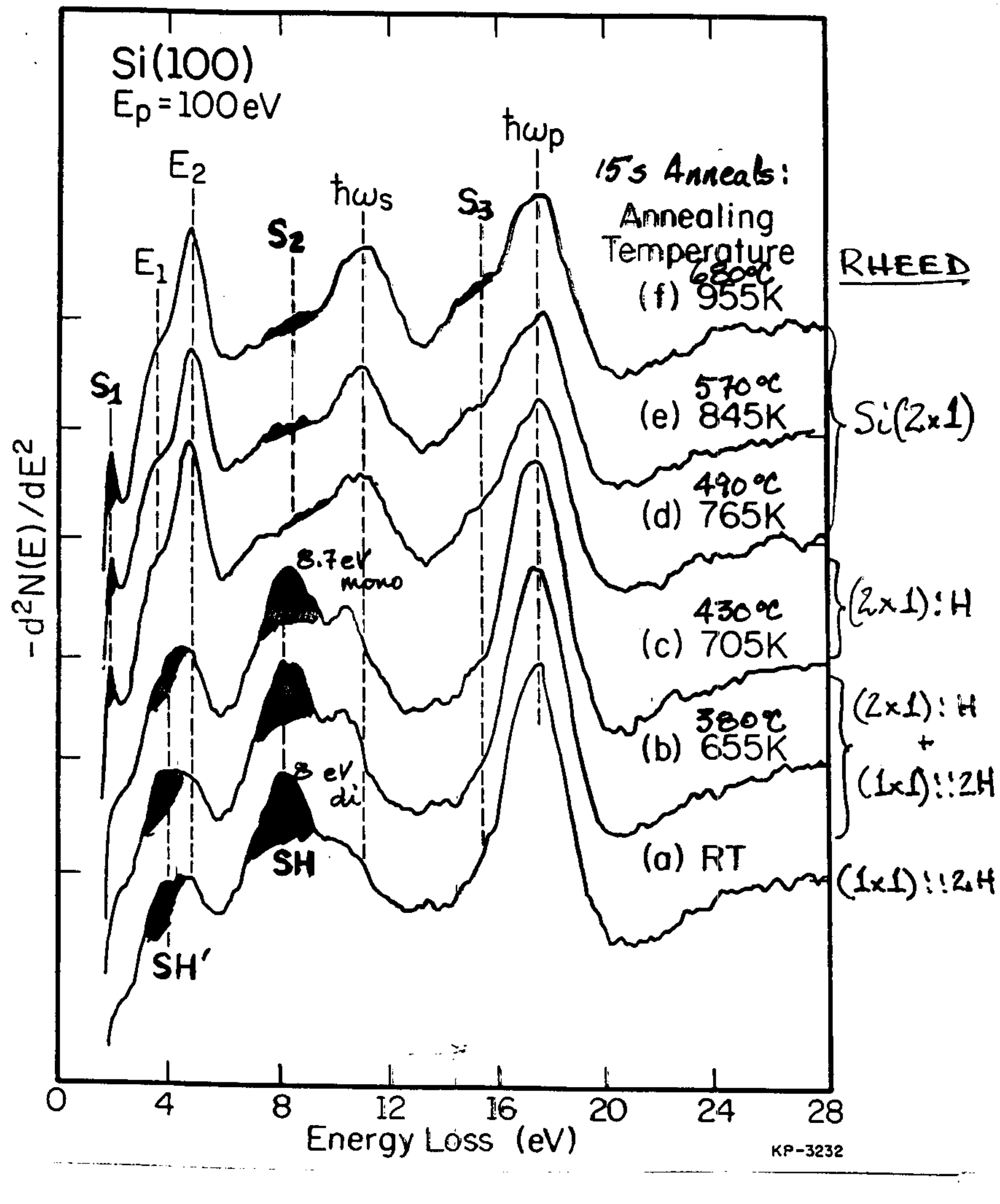


Figure 4. EELS spectra, obtained using a primary electron energy E_p of 100 eV, from a Si_2H_6-saturated Si(100) (1x1)::2H dihydride surface following a 15 s anneal at (a) 300 K, (b) 655 K, (c) 705 K, (d) 765 K, (e) 845 K, and (f) 955 K.

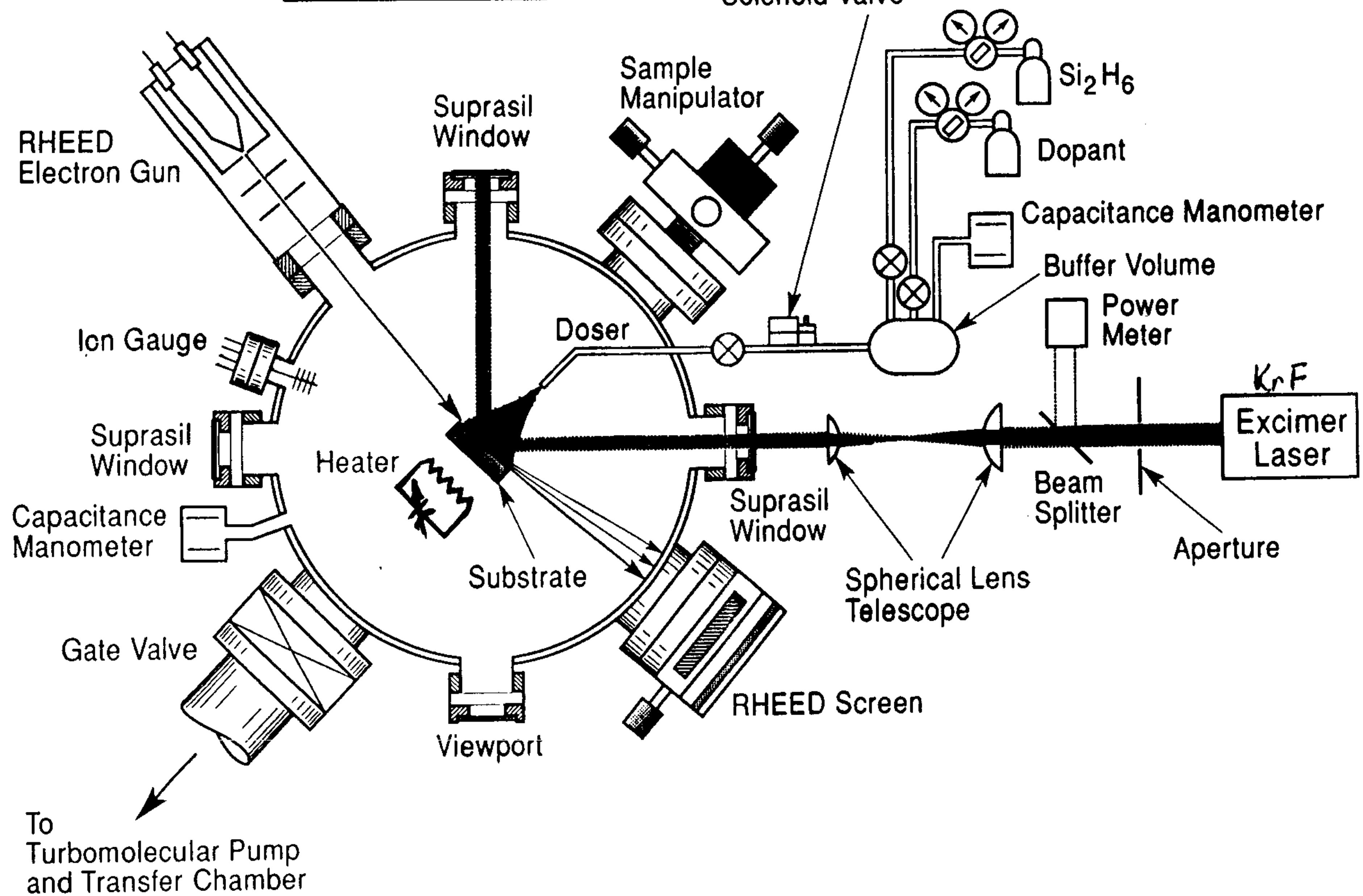
Si_2H_6 dose = 3.2×10^{14} cm^{-2}

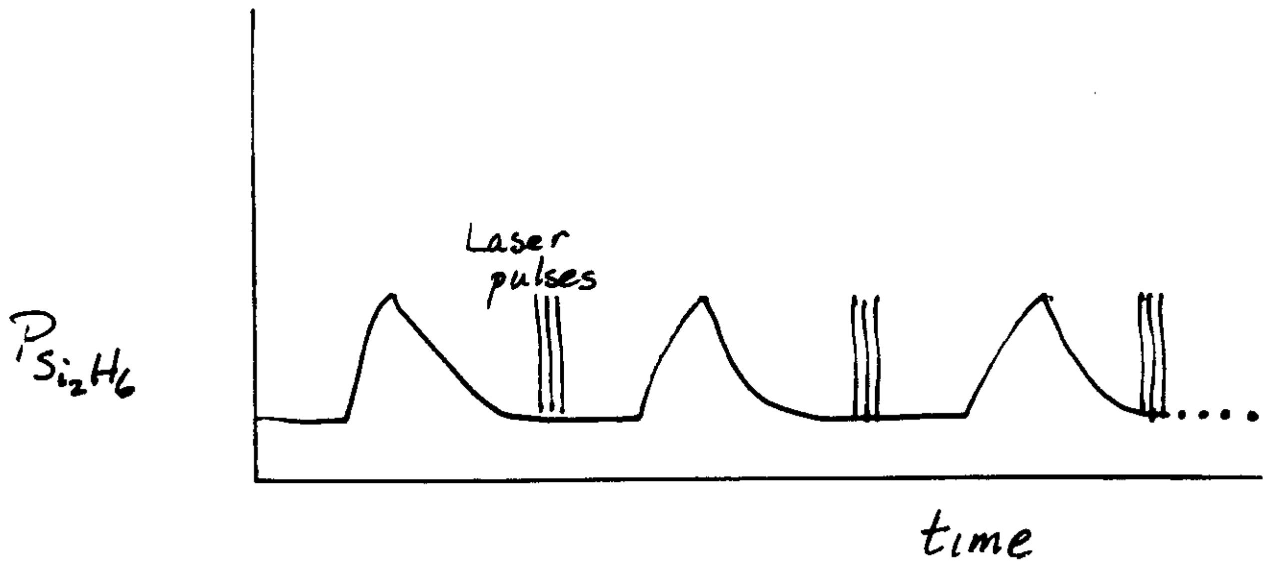
T_s = 380 °C

200 Å × 200 Å

Lin, Hirchorn, Chuang, Tsu, Lubben, Greene
Phys. Rev. B

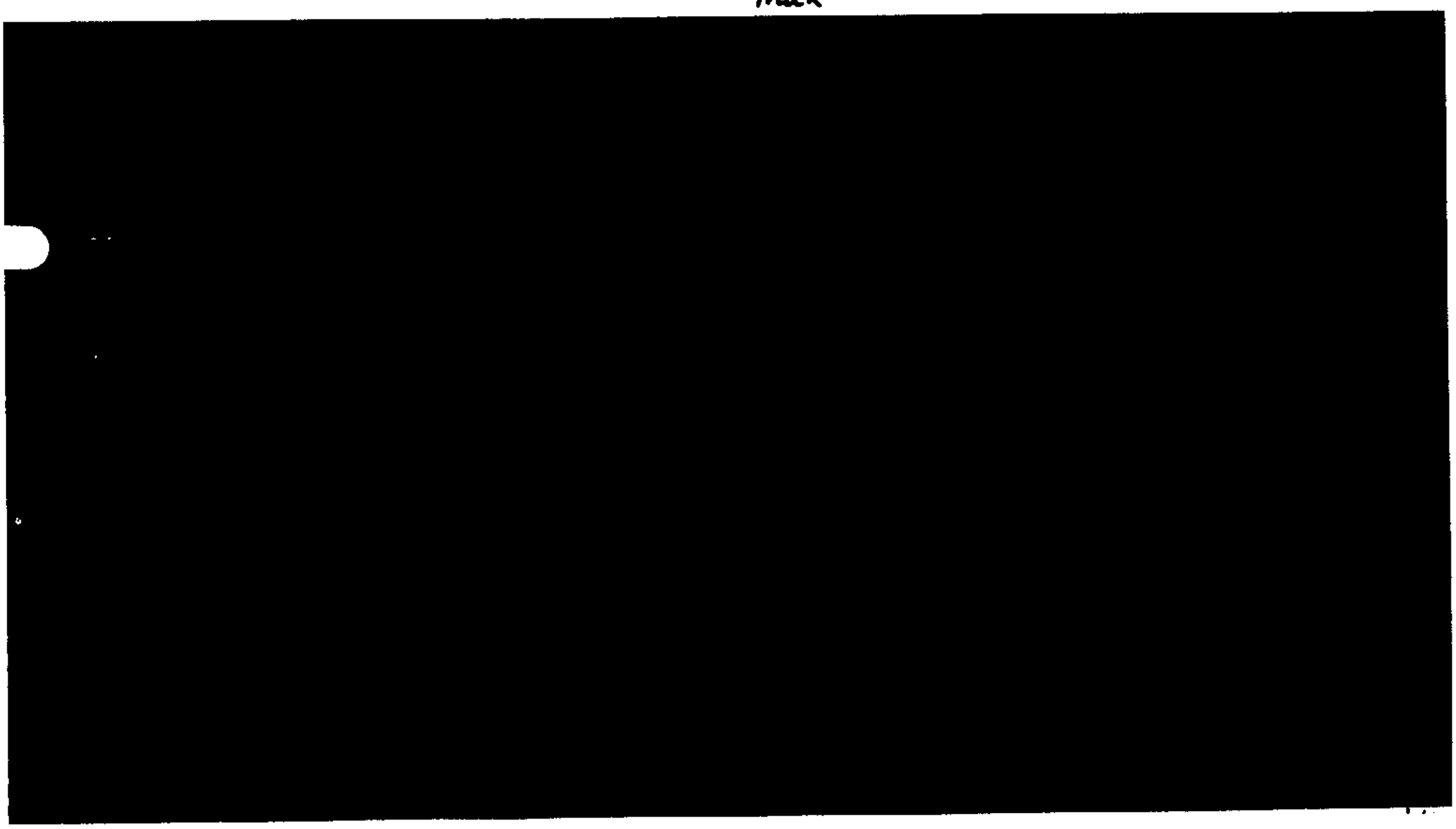
Si ALE System

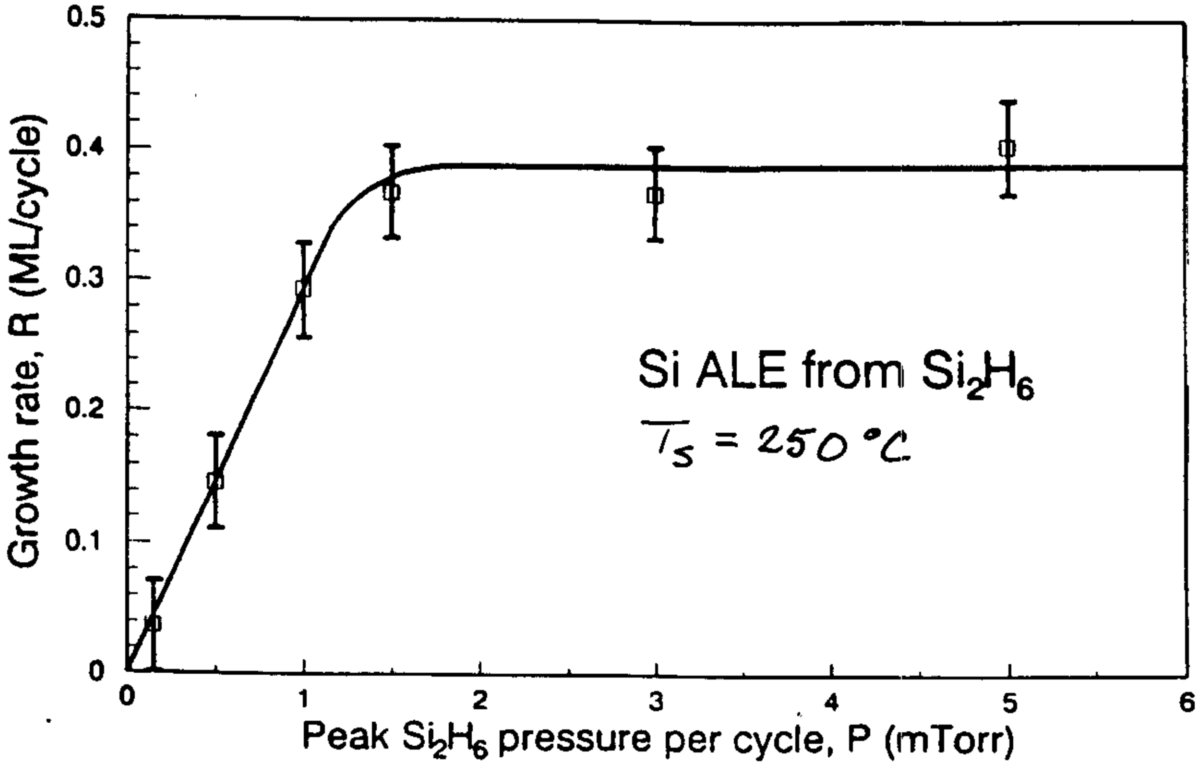


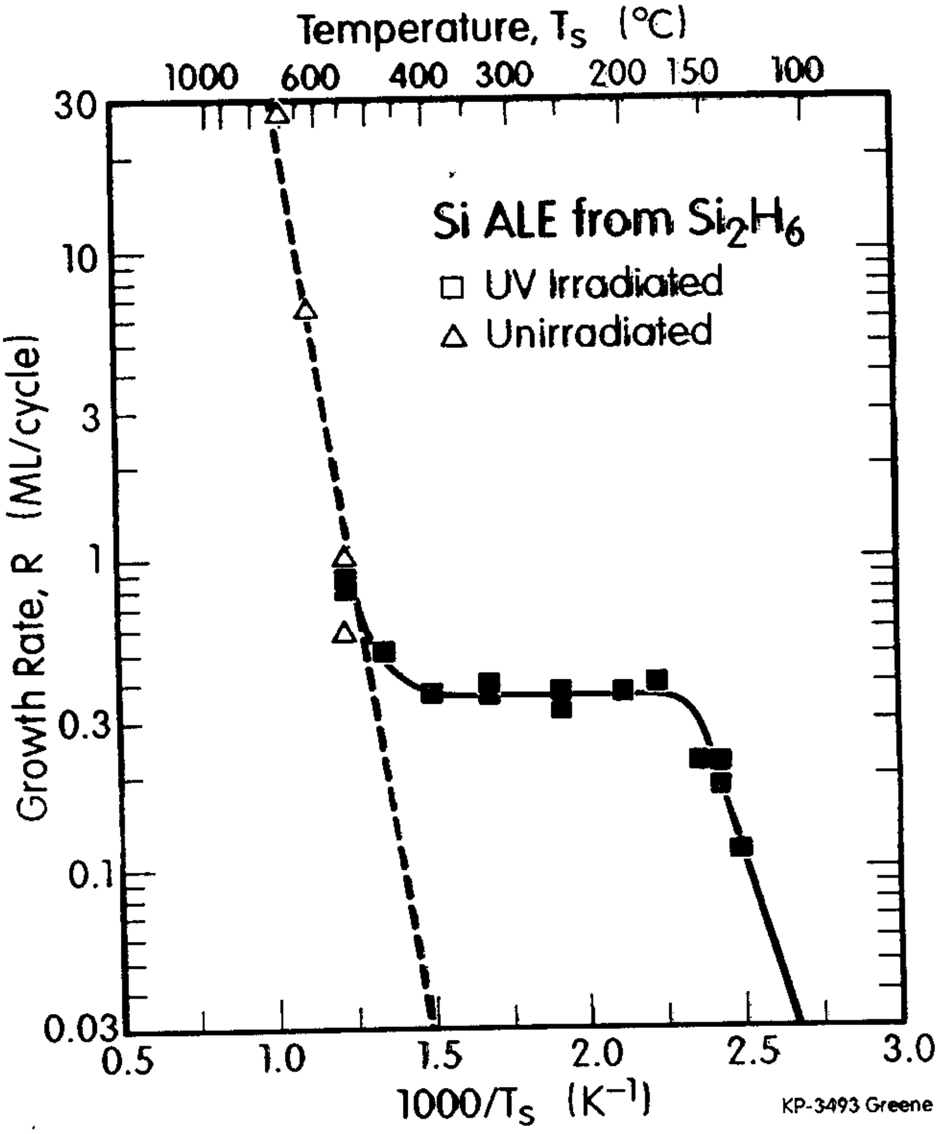


$180\,°C \leq T_s \leq 400\,°C$

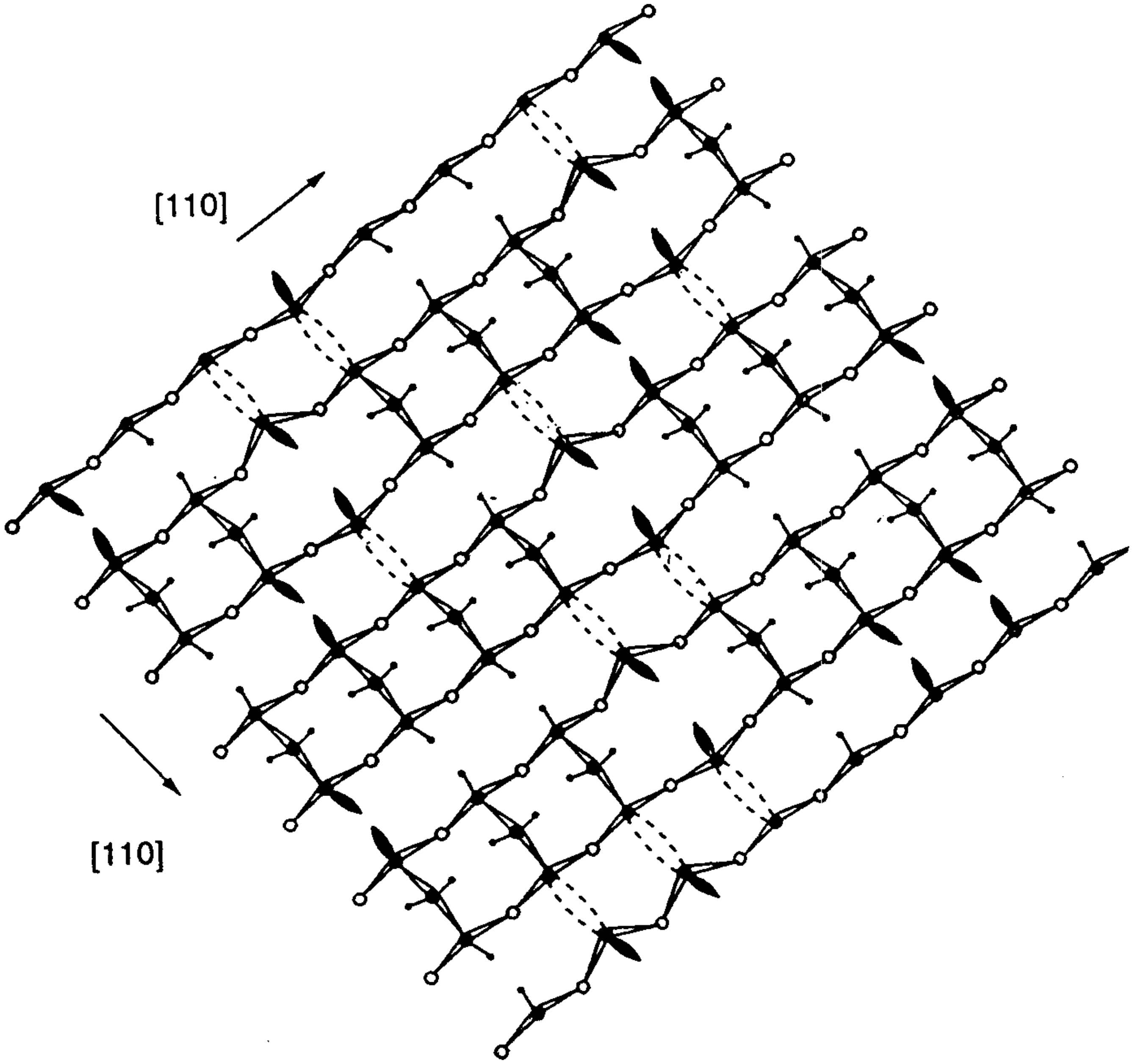
$P_{max} \gtrsim 1.5$ mTorr




0.5
0.4
0.3
0.2
0.1
0
Growth rate, R (ML/cycle)
0
1
2
3
4
5
6
Peak Si2H6 pressure per cycle, P (mTorr)
Si ALE from Si2H6
Ts = 250 °C

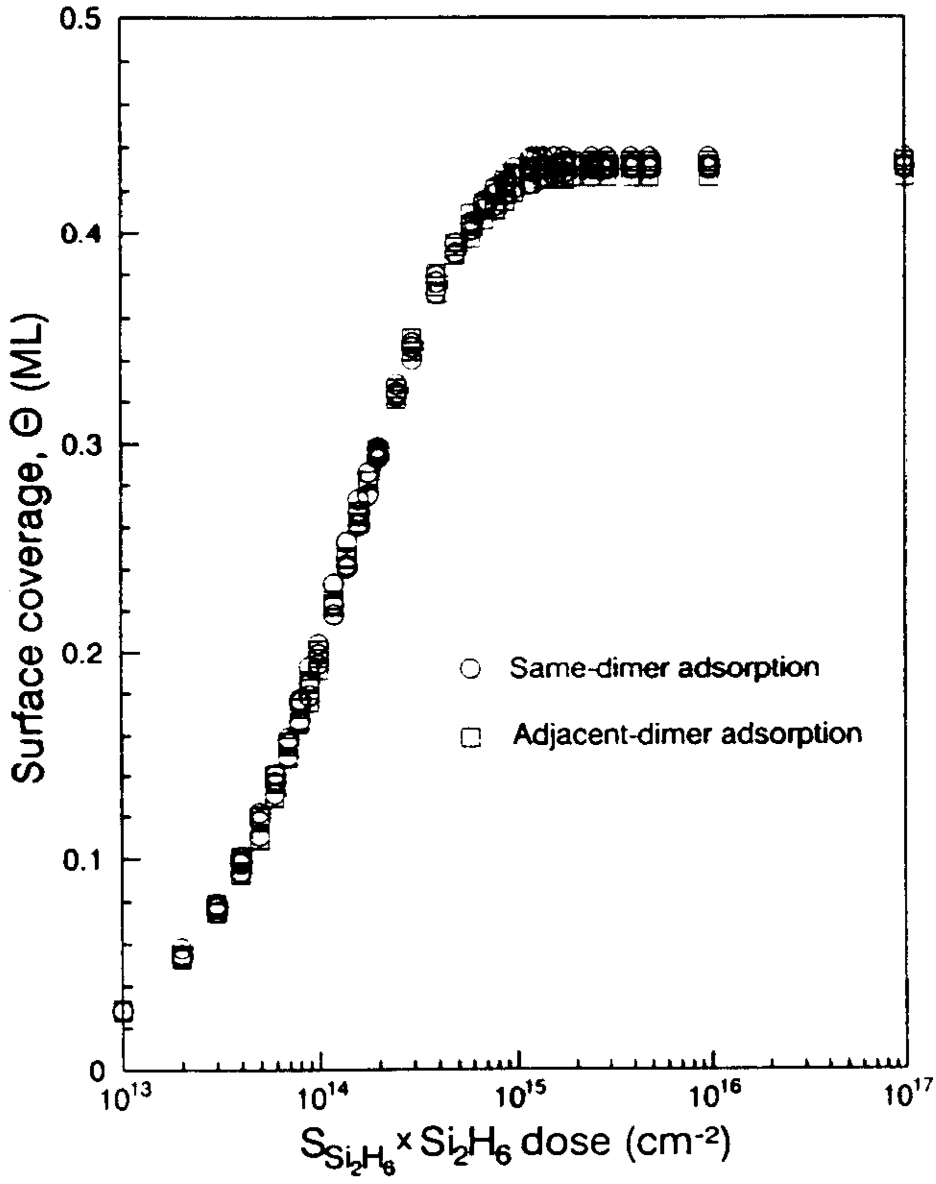


Lubben, Tsu, Bramblett, Greene, JVST A



• = Surface Si atom
• = Adsorbed Si atom
= H atom
= Dangling bond
= Si-Si bond

D.S. Lin, T.-C. Chiang, R. Tsu, J.E. Greene, Phys. Rev. B, in press.


0.5
0.4
0.3
0.2
0.1
0
Surface coverage, Θ (ML)
Same-dimer adsorption
Adjacent-dimer adsorption
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
$S_{Si_2H_6}$ x Si_2H_6 dose (cm^{-2})

Analytical Transition-State Model

Si(001)2x1 ALE

$$\frac{dn_{SiH_3}}{dt} = 2\, J_{Si_2H_6}\, S_{Si_2H_6}(T_s)\left[1 - N_{oc} - N_{bl}\right] - n_{SiH_3} k_{d,SiH_3} - (n_{SiH_3})^2 k_{a,Si_2H_6} - \underline{n_{SiH_3} k_{dis,SiH_3}}$$

$$\frac{dn_{SiH_2}}{dt} = \underline{n_{SiH_3} k_{dis,SiH_3}} - n_{SiH_2} k_{d,SiH_2} - n_{SiH_2} k_{dis,SiH_2}$$

$$\underline{k_{dis,SiH_3}} = \nu\, e^{(-E_{dis,SiH_3}/kT_s)}$$

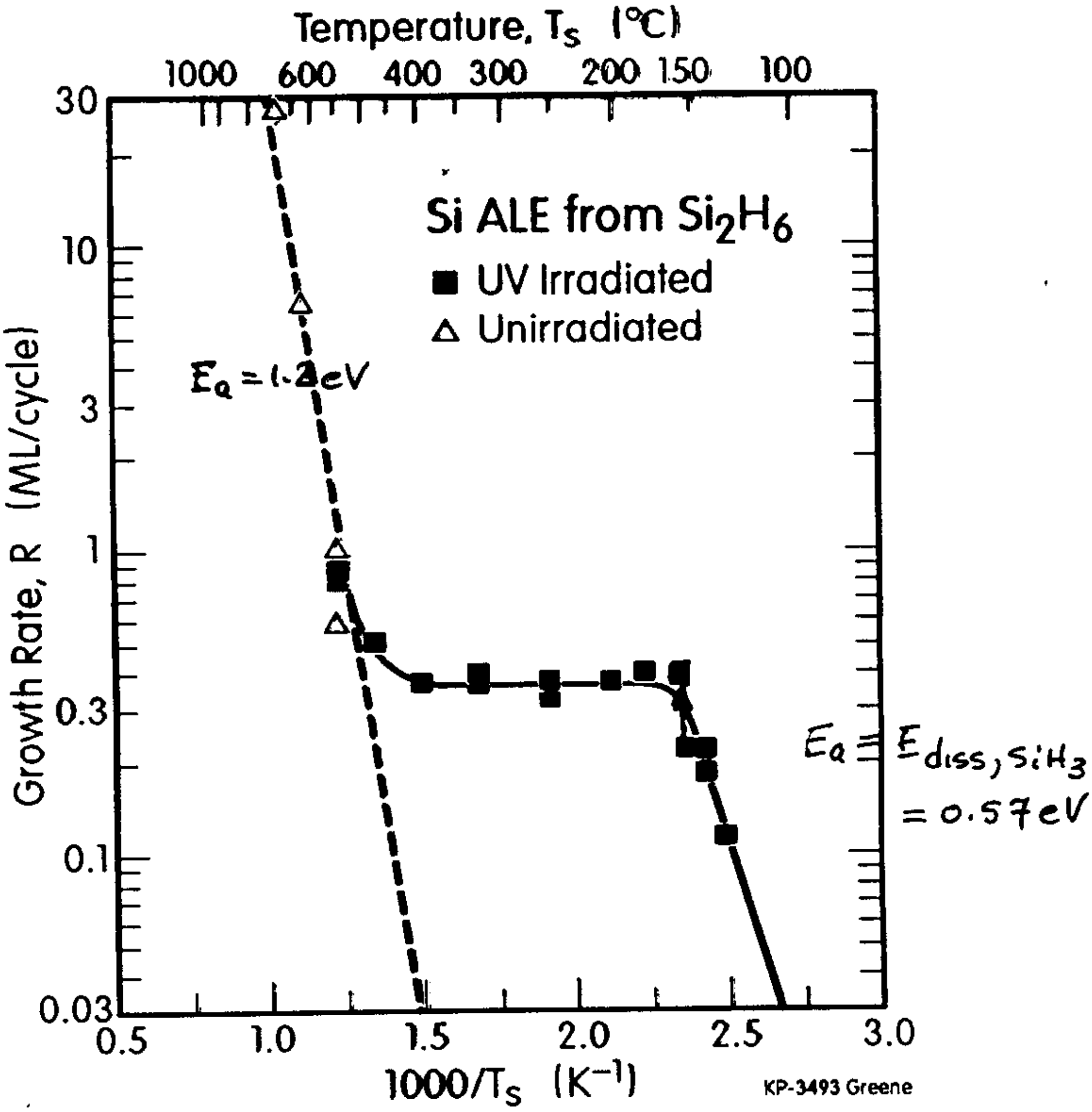
$$N_{un} + N_{oc} + N_{bl} = 1$$

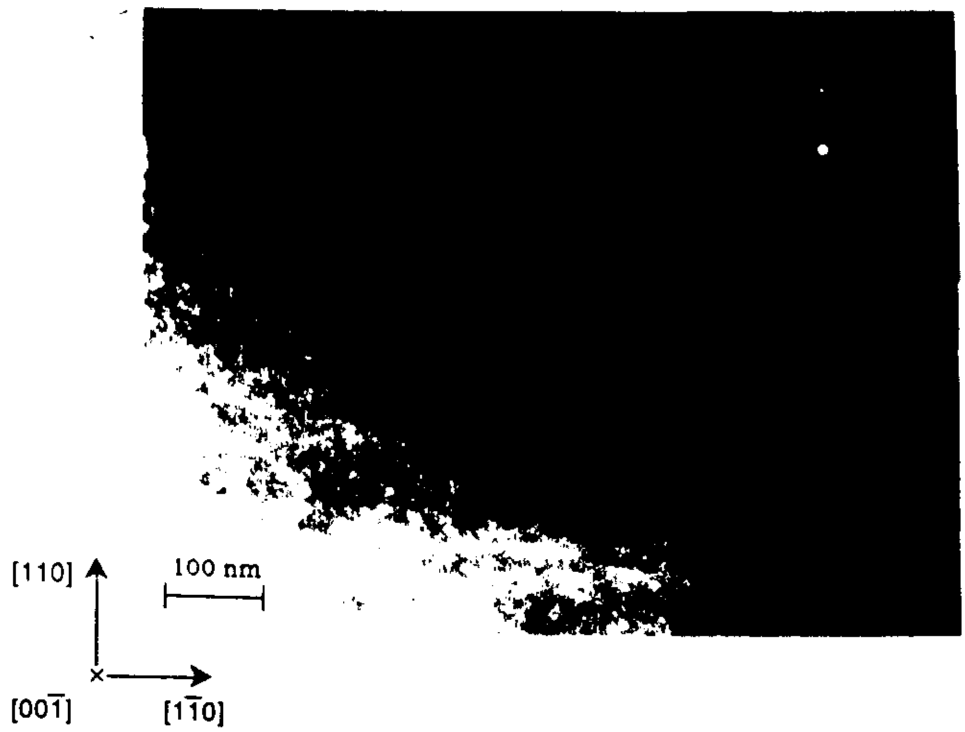
Monte Carlo simulation → $N_{bl} = f(N_{oc})$

$$n^*_{SiH_3} \simeq 0.4\, n_s - n^*_{SiH_2}$$

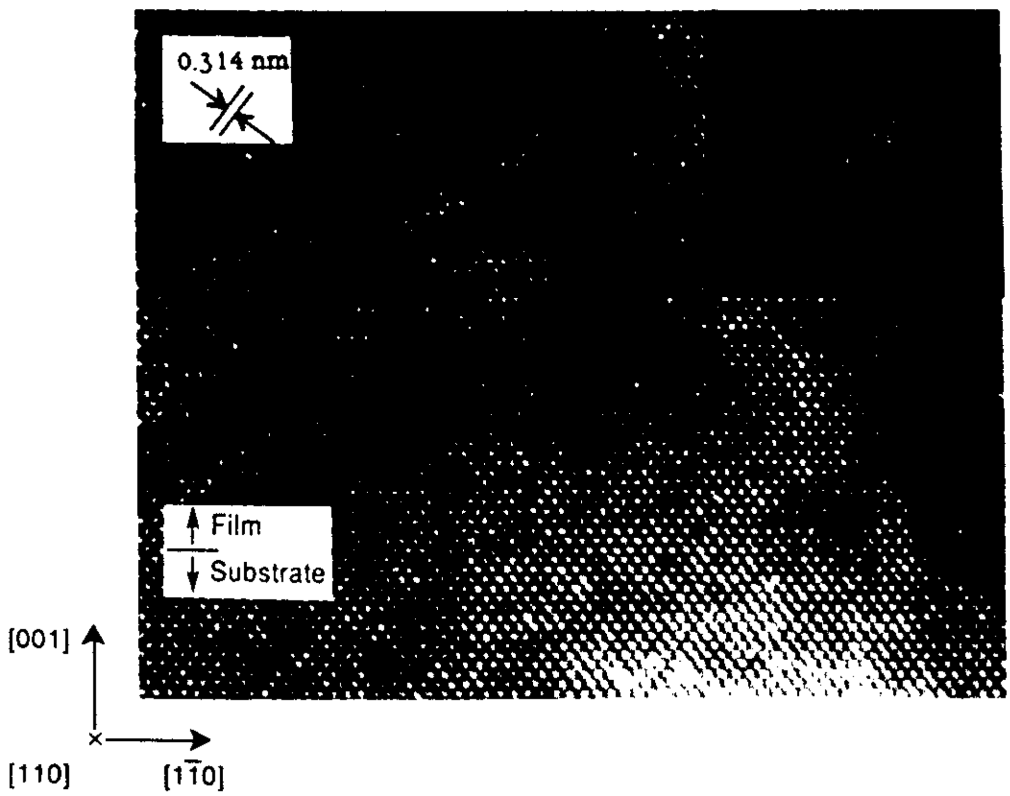
$$\boxed{n^*_{SiH_2} = 0.4\, n_s\, \underline{\Delta t}\, \nu\, e^{(-\underline{E_{dis,SiH_3}}/kT_s)}}$$

∴ ALE : $R = n^*_{Si} = n^*_{SiH_2} \simeq 0.4$ ML/cycle

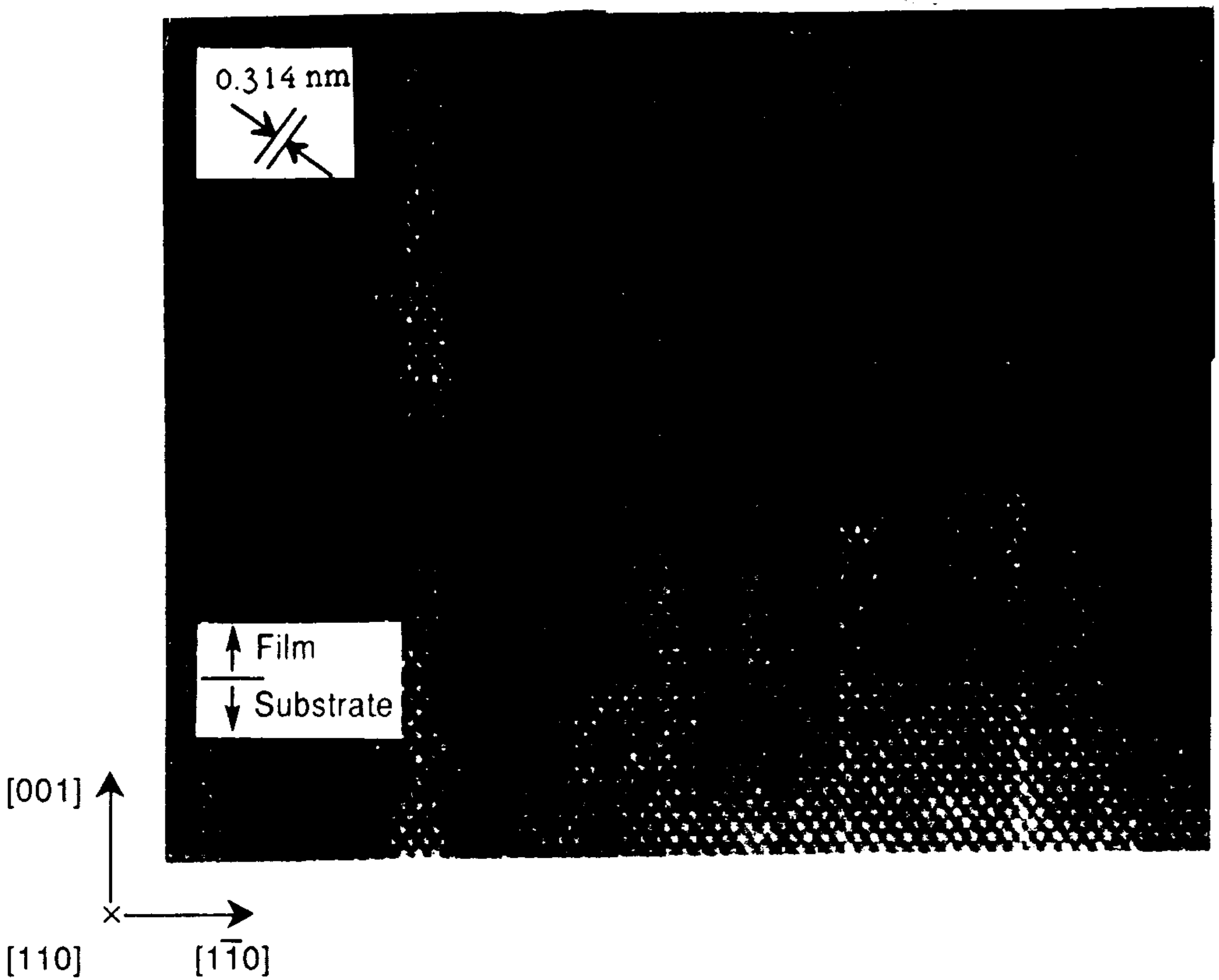

Temperature, T_S (°C)
1000 600 400 300 200 150 100
Si ALE from Si_2H_6
UV Irradiated
Unirradiated
E_a = 1.2 eV
$E_a \equiv E_{diss, SiH_3}$ = 0.57 eV
Growth Rate, R (ML/cycle)
30 10 3 1 0.3 0.1 0.03
0.5 1.0 1.5 2.0 2.5 3.0
1000/T_S (K^{-1})
KP-3493 Greene



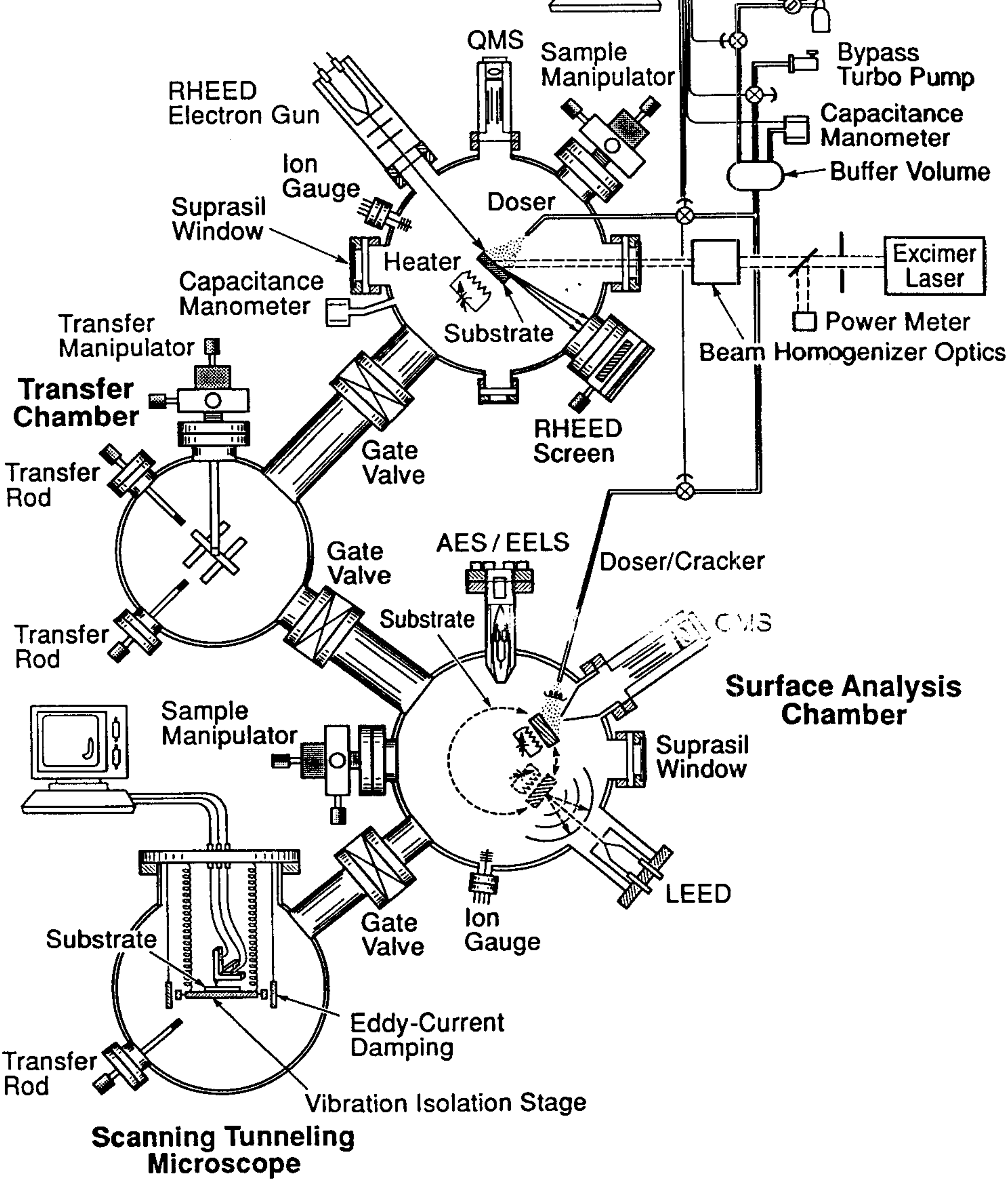
Plan-view

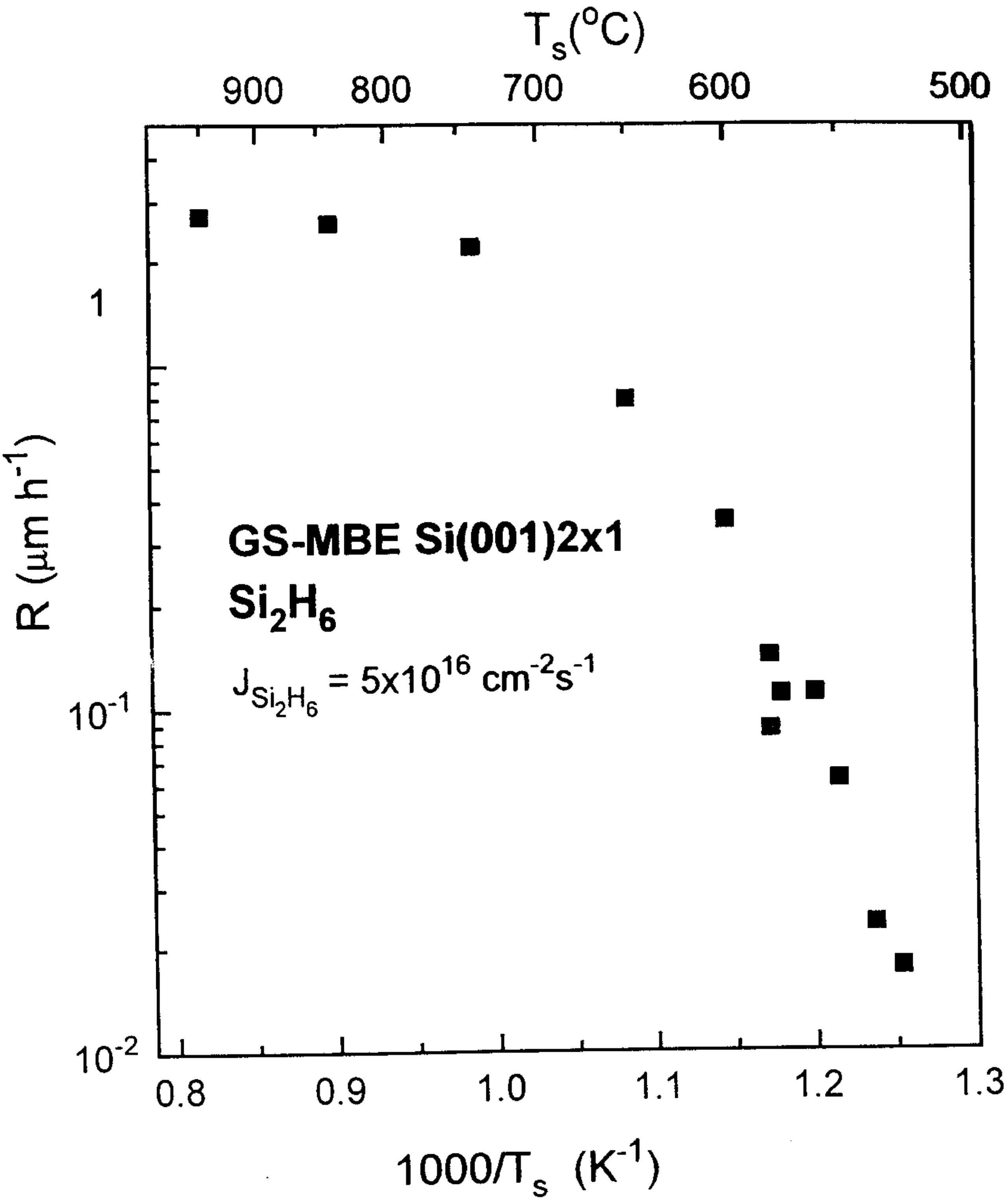


Cross-section


0.314 nm
Film
Substrate
[001]
[110]
[1$\bar{1}$0]

UV Photostimulated ALE and Gas Source MBE System





$T_s(^oC)$
900
800
700
600
500
1
10^{-1}
10^{-2}
$R\ (\mu m\ h^{-1})$
GS-MBE Si(001)2x1
Si_2H_6
$J_{Si_2H_6} = 5x10^{16}\ cm^{-2}s^{-1}$
0.8
0.9
1.0
1.1
1.2
1.3
$1000/T_s\ (K^{-1})$

$$Si_2H_6 + 2\,db \xrightarrow{k_a} 2\,SiH_3(a) \qquad 2\times1$$

$$SiH_3(a) + db \longrightarrow SiH_2(a) + H(a) \qquad 1\times1$$

$$2\;SiH_2(a) \longrightarrow (SiH)_2\,(a) + H_2\uparrow \qquad 2\times1$$

$$SiH(a) \xrightarrow{k_d} \tfrac{1}{2}H_2\uparrow + db \qquad 1\times1$$

$$\frac{d\theta_{db}}{dt} = -2k_a J_{Si_2H_6}\,\theta_{db}^2 + k_d(1-\theta_{db})$$

∴ at steady state:

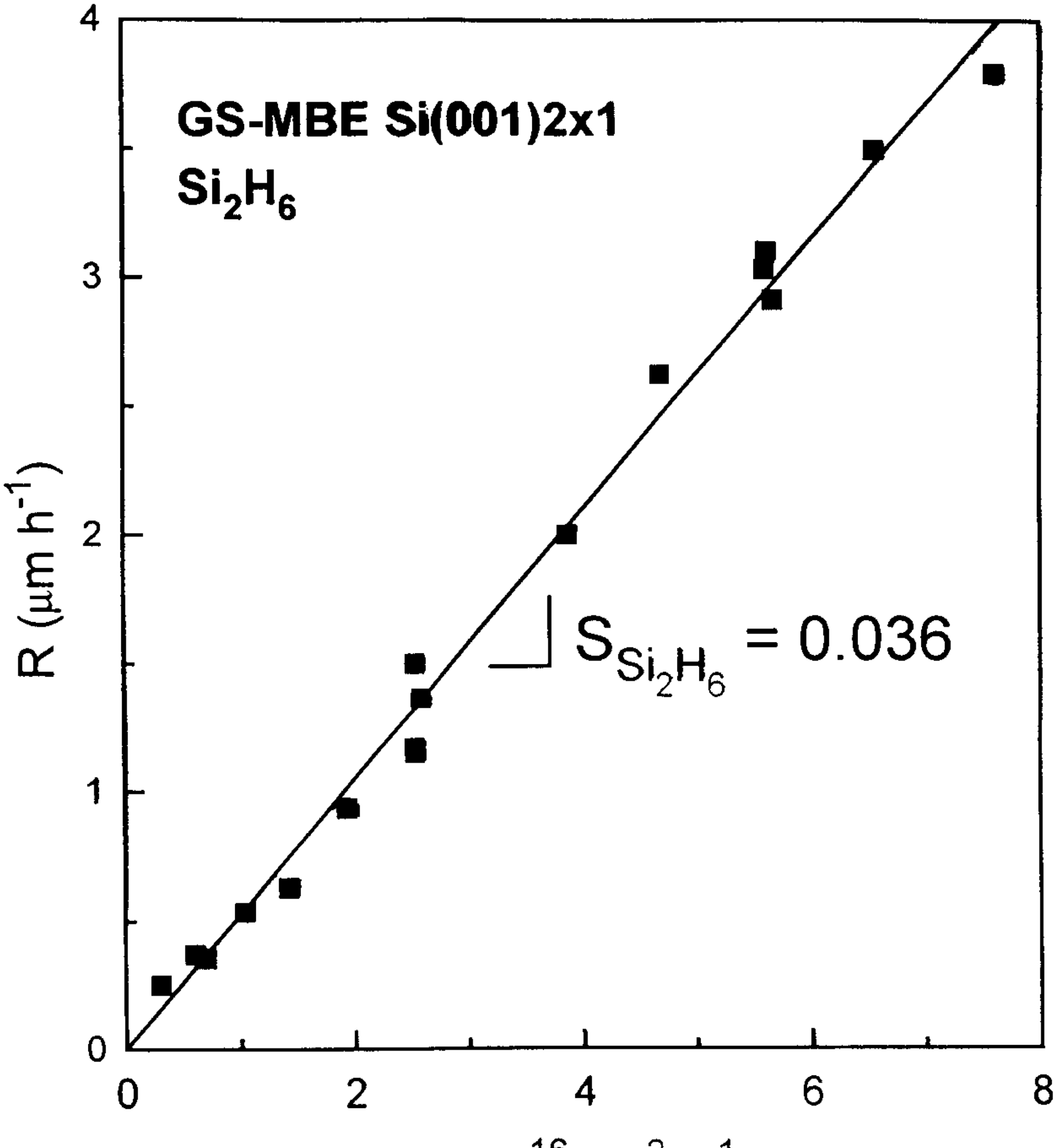
$$\theta_{db} = \frac{k_d}{4k_a J_{Si_2H_6}}\left[\left(1+\frac{8k_a J_{Si_2H_6}}{k_d}\right)^{1/2} - 1\right]$$

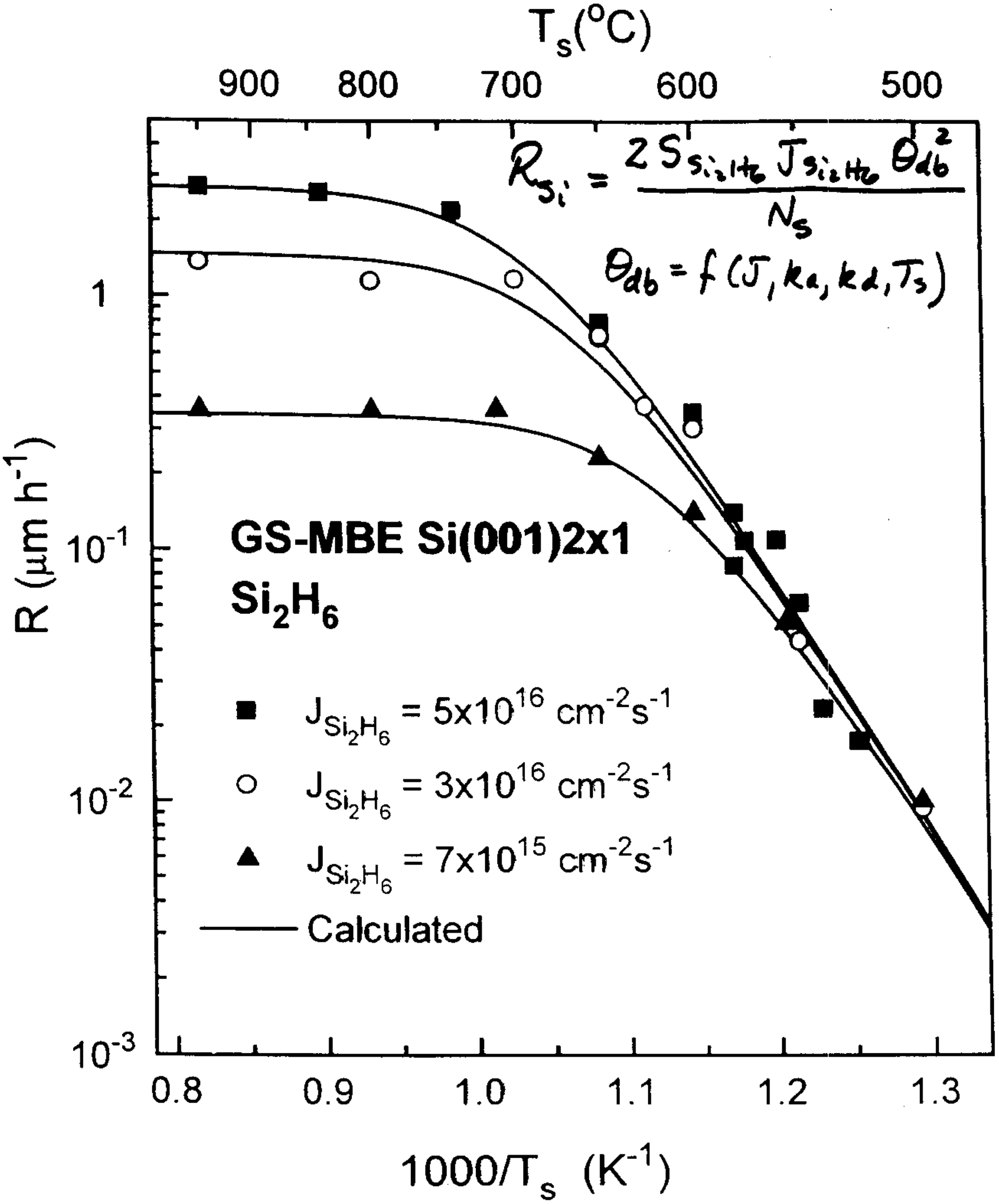
$$\boxed{R = \frac{2N_s k_a J_{Si_2H_6}\,\theta_{db}^2}{N}}$$

where $k_a = S_{Si_2H_6}/N_s$ (measured)

$k_d = 7.9\times10^{11}\exp\left(\frac{2.04\,eV}{kT_s}\right)\ s^{-1}$

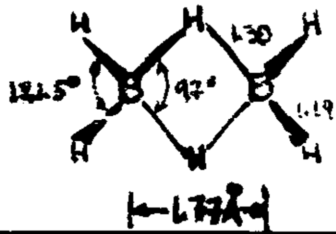
(Yates et. al., JCP 92, 5700 (1990)).

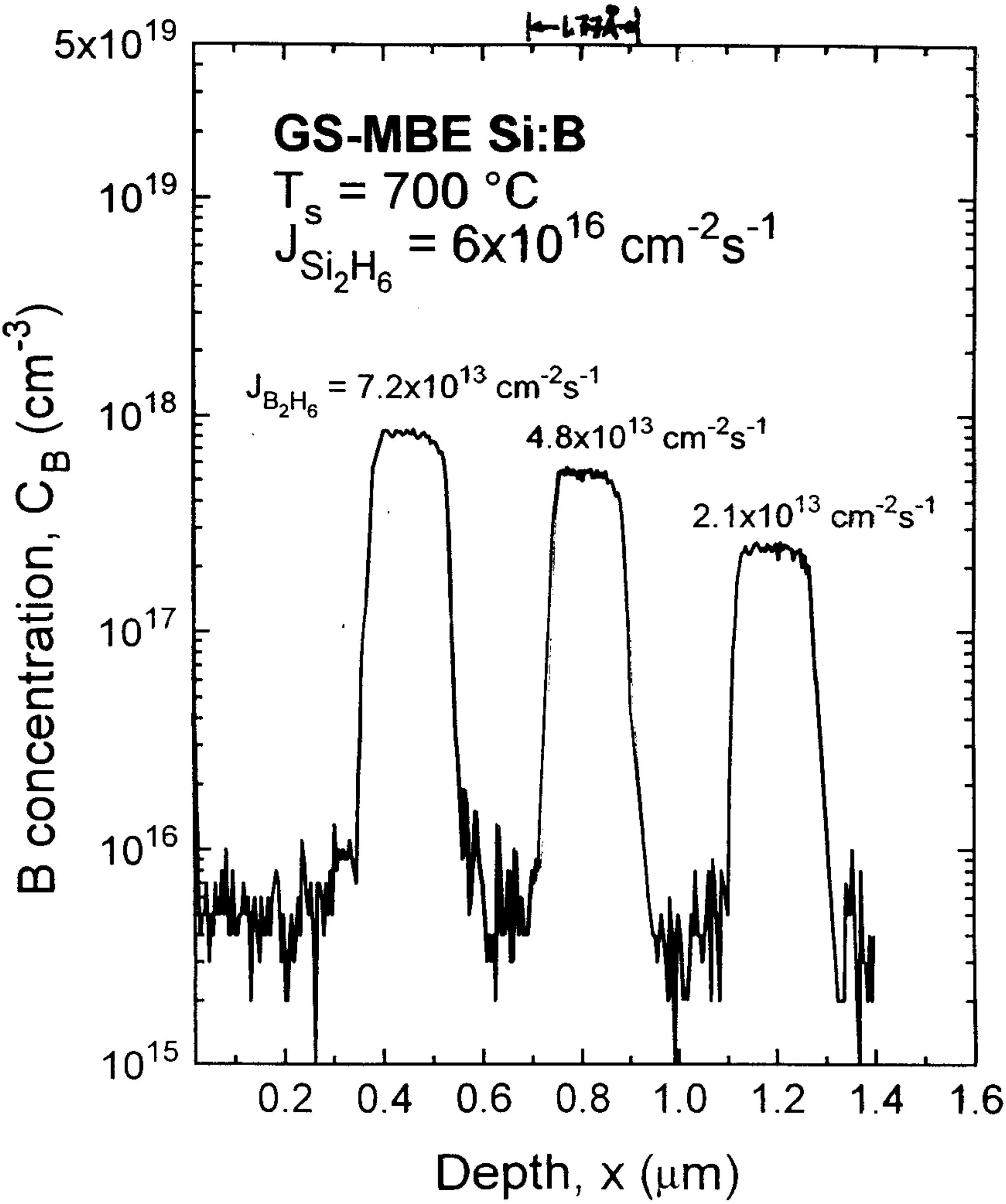

GS-MBE Si(001)2x1
Si2H6
S Si2H6 = 0.036
R (μm h-1)
J (10^16 cm-2 s-1)
0
1
2
3
4
0
2
4
6
8



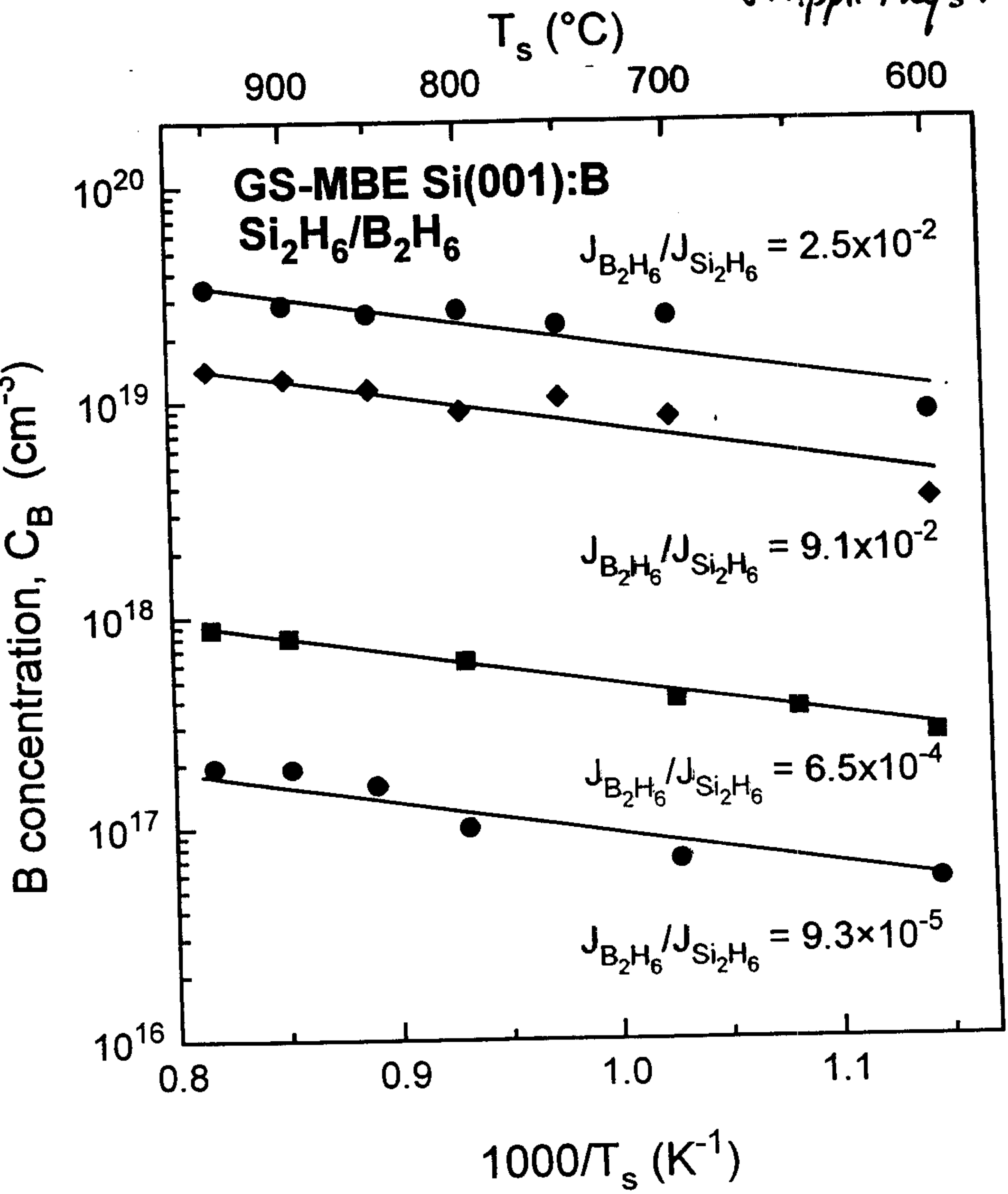
T.R. Bramblett, Q. Lu, T. Karasawa, M.-A. Hasan, S.K. Jo, and J.E. Greene, J. Appl. Phys.

Diborane:

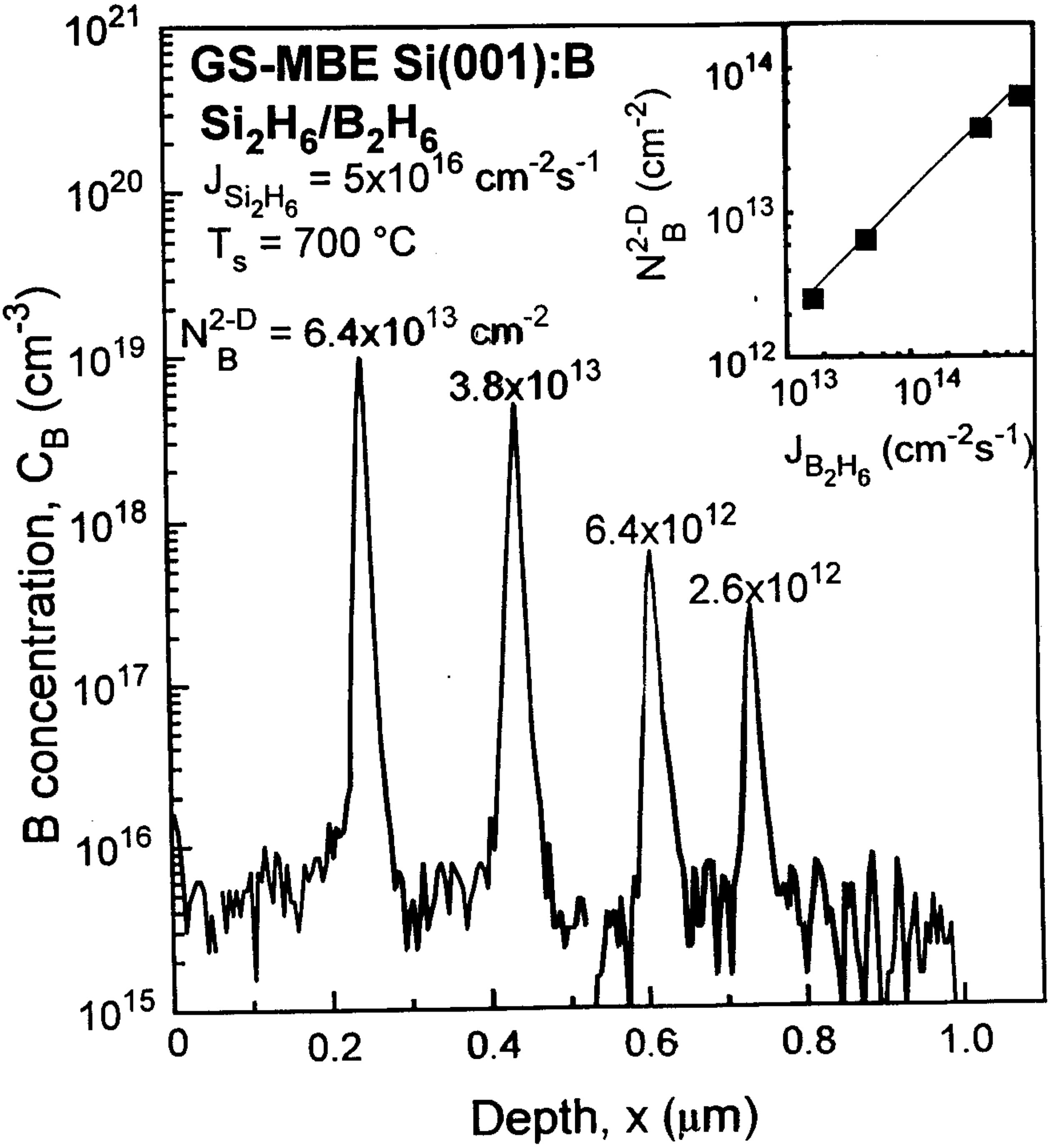

H
H
1.30
H
121.5°
97°
1.19
H
H
H
1.77Å

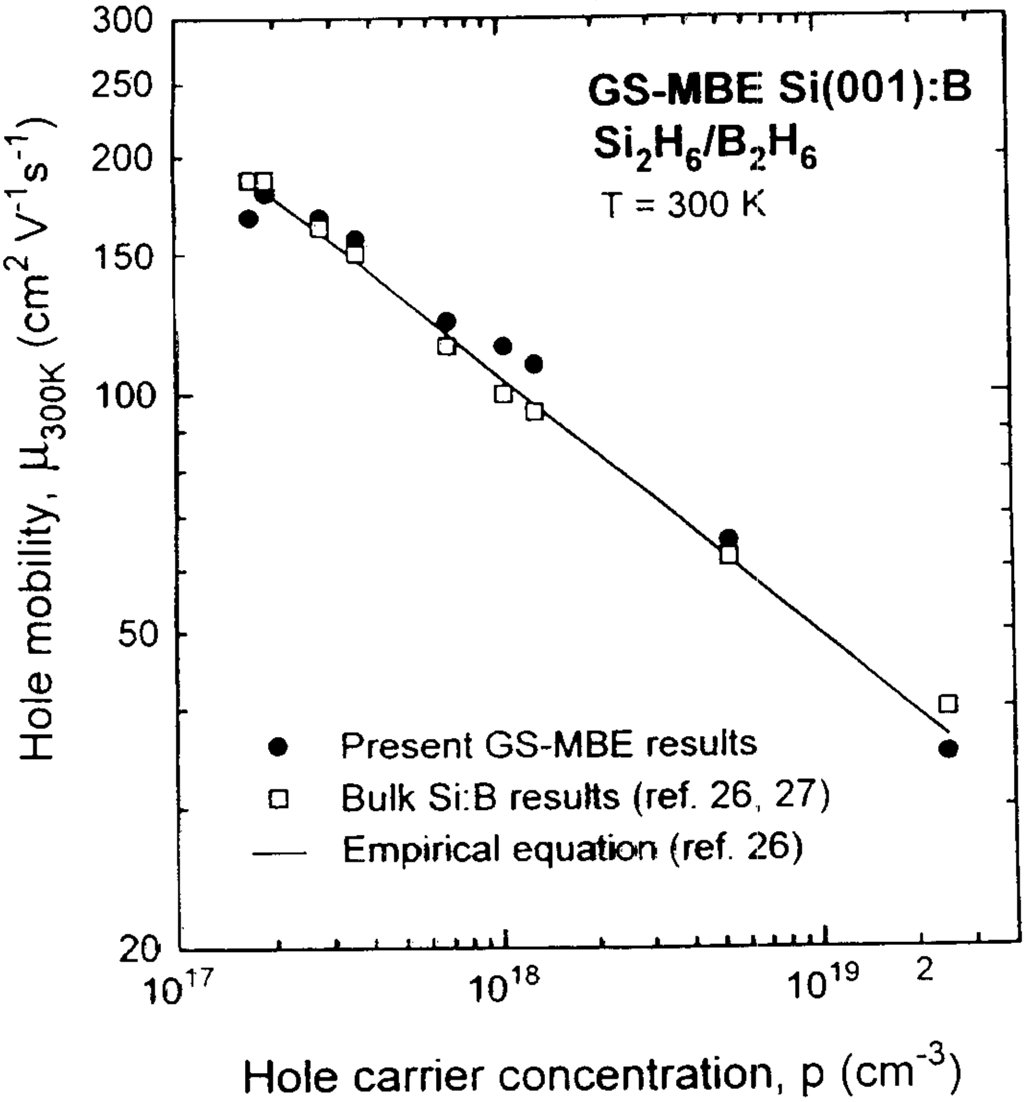

GS-MBE Si:B
T_s = 700 °C
$J_{Si_2H_6}$ = 6x10^{16} cm^{-2}s^{-1}
$J_{B_2H_6}$ = 7.2x10^{13} cm^{-2}s^{-1}
4.8x10^{13} cm^{-2}s^{-1}
2.1x10^{13} cm^{-2}s^{-1}
B concentration, C_B (cm^{-3})
5x10^{19}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Depth, x (μm)

Lu, Bramblett, Lee, Hasan, Kavasawa, Greene
J. Appl. Phys.

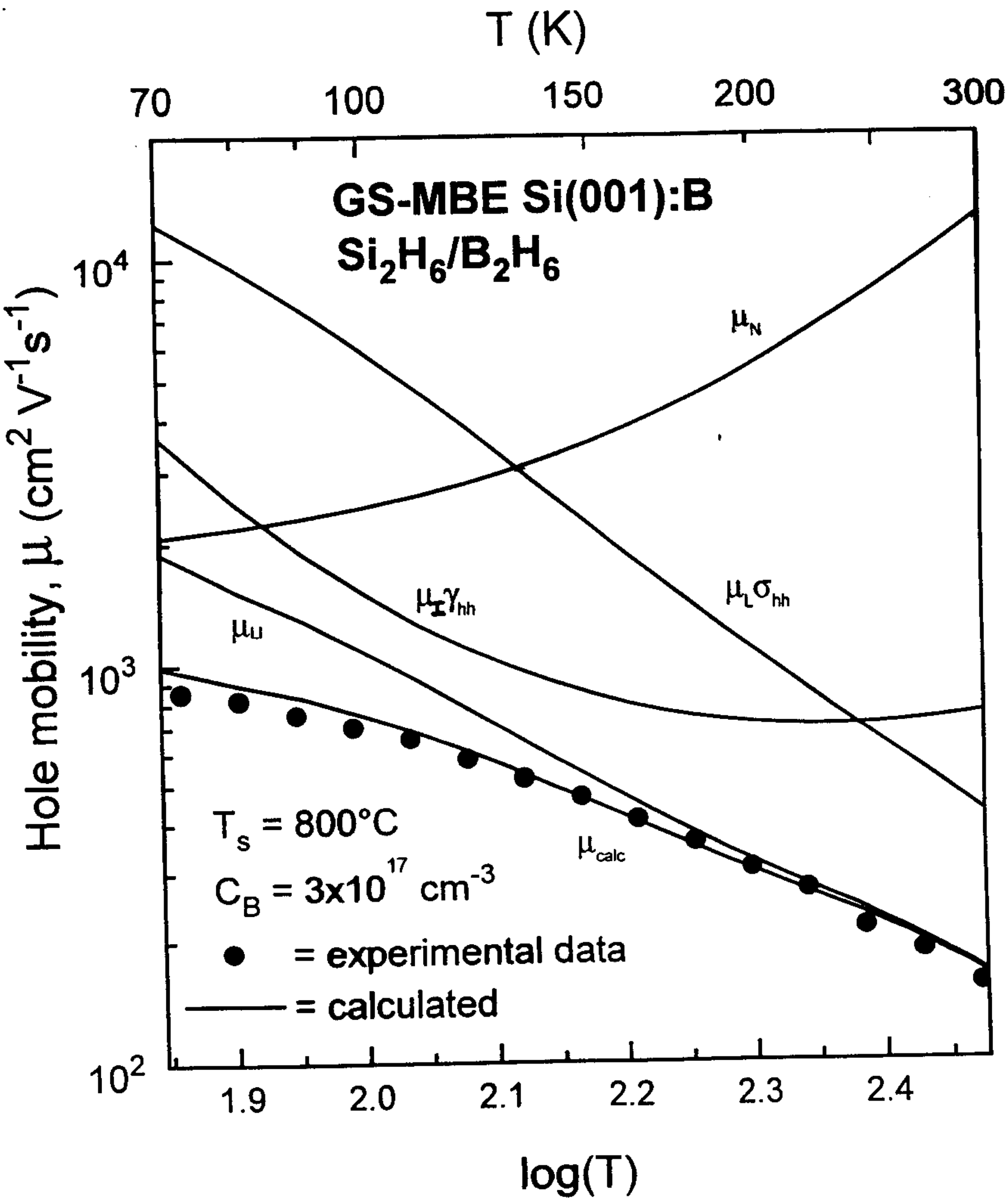


$S_{B_2H_6/Si(001)}$ = 6.4×10^{-4} @ 600°C
1.4×10^{-3} 950°C

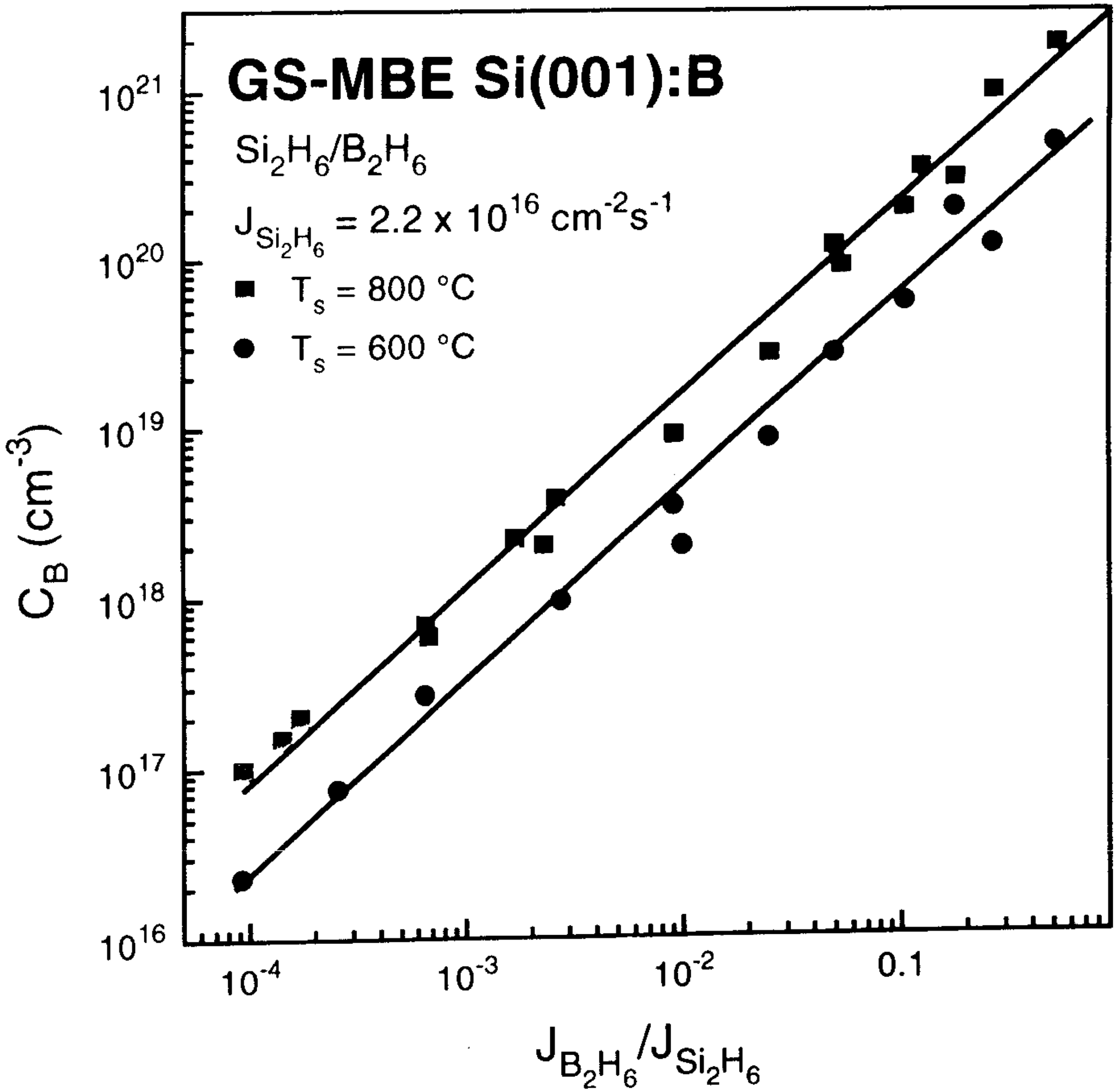

GS-MBE Si(001):B
Si2H6/B2H6
JSi2H6 = 5x10^16 cm^-2s^-1
Ts = 700 °C
NB2-D = 6.4x10^13 cm^-2
3.8x10^13
6.4x10^12
2.6x10^12
B concentration, CB (cm^-3)
Depth, x (μm)
NB2-D (cm^-2)
JB2H6 (cm^-2s^-1)
10^21
10^20
10^19
10^18
10^17
10^16
10^15
0
0.2
0.4
0.6
0.8
1.0
10^14
10^13
10^12
10^13
10^14

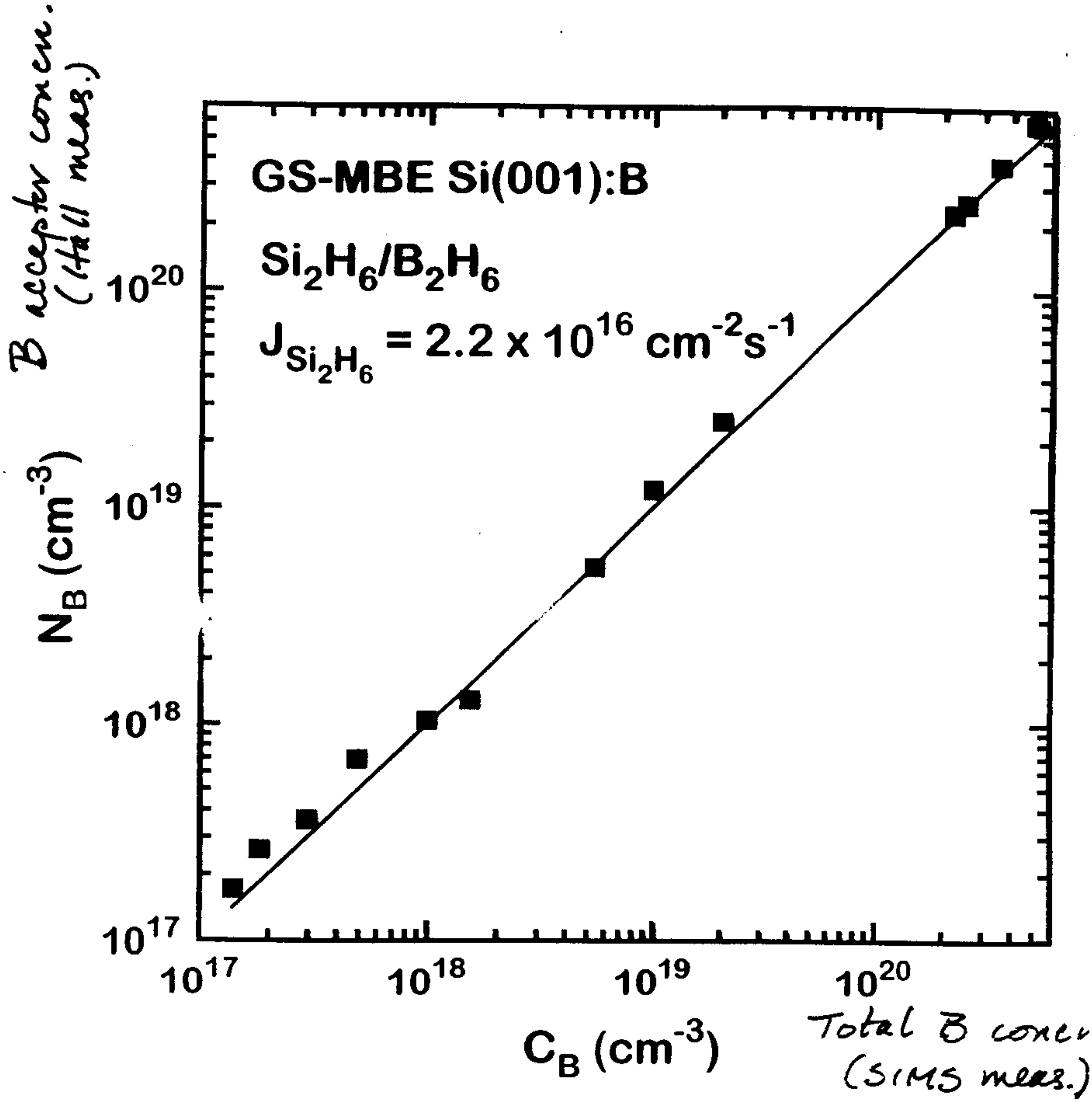


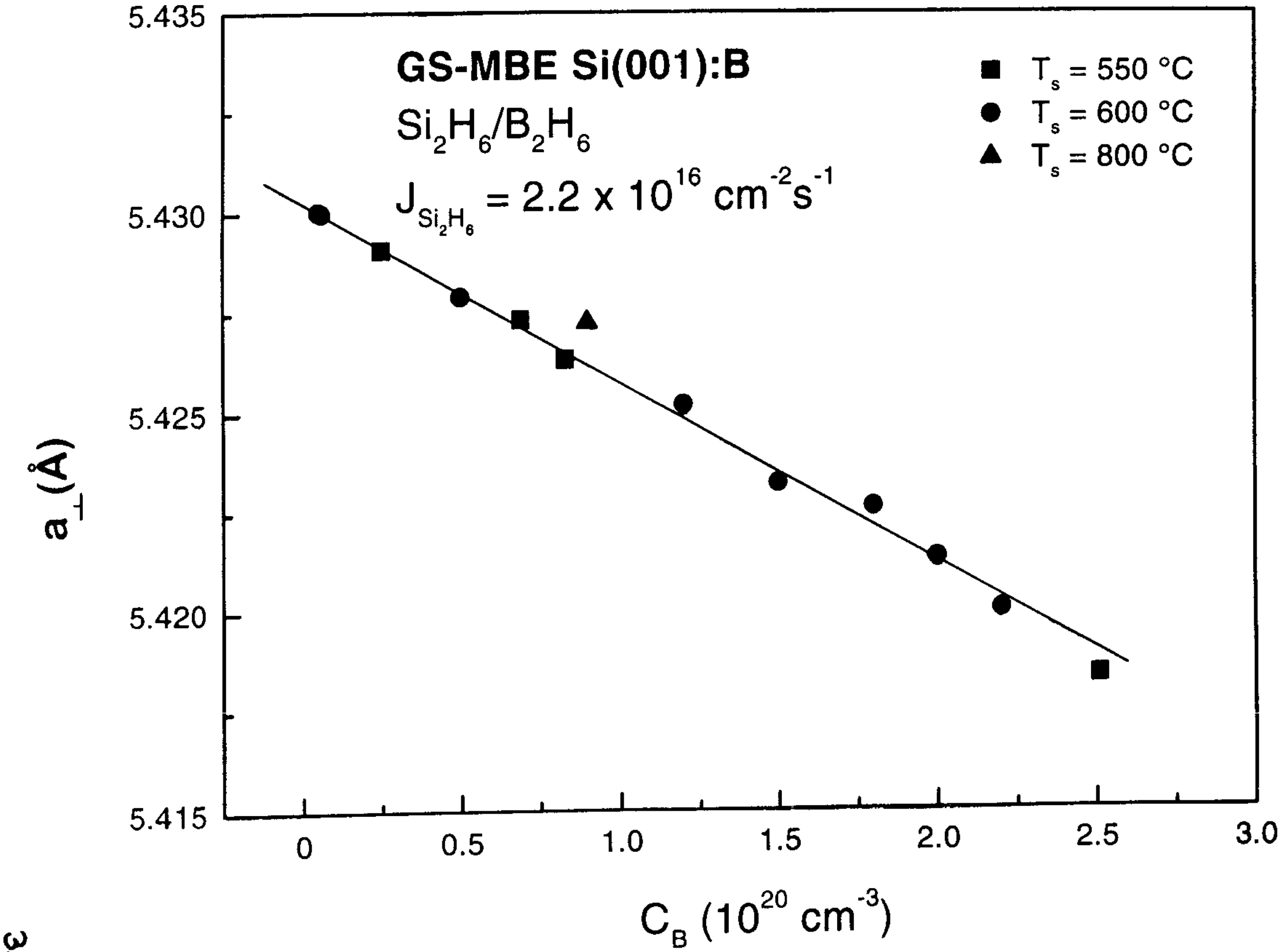
GS-MBE Si(001):B
Si_2H_6/B_2H_6
T = 300 K
Present GS-MBE results
Bulk Si:B results (ref. 26, 27)
Empirical equation (ref. 26)
Hole mobility, μ_{300K} ($cm^2 V^{-1} s^{-1}$)
300
250
200
150
100
50
20
10^{17}
10^{18}
10^{19}
2
Hole carrier concentration, p (cm^{-3})

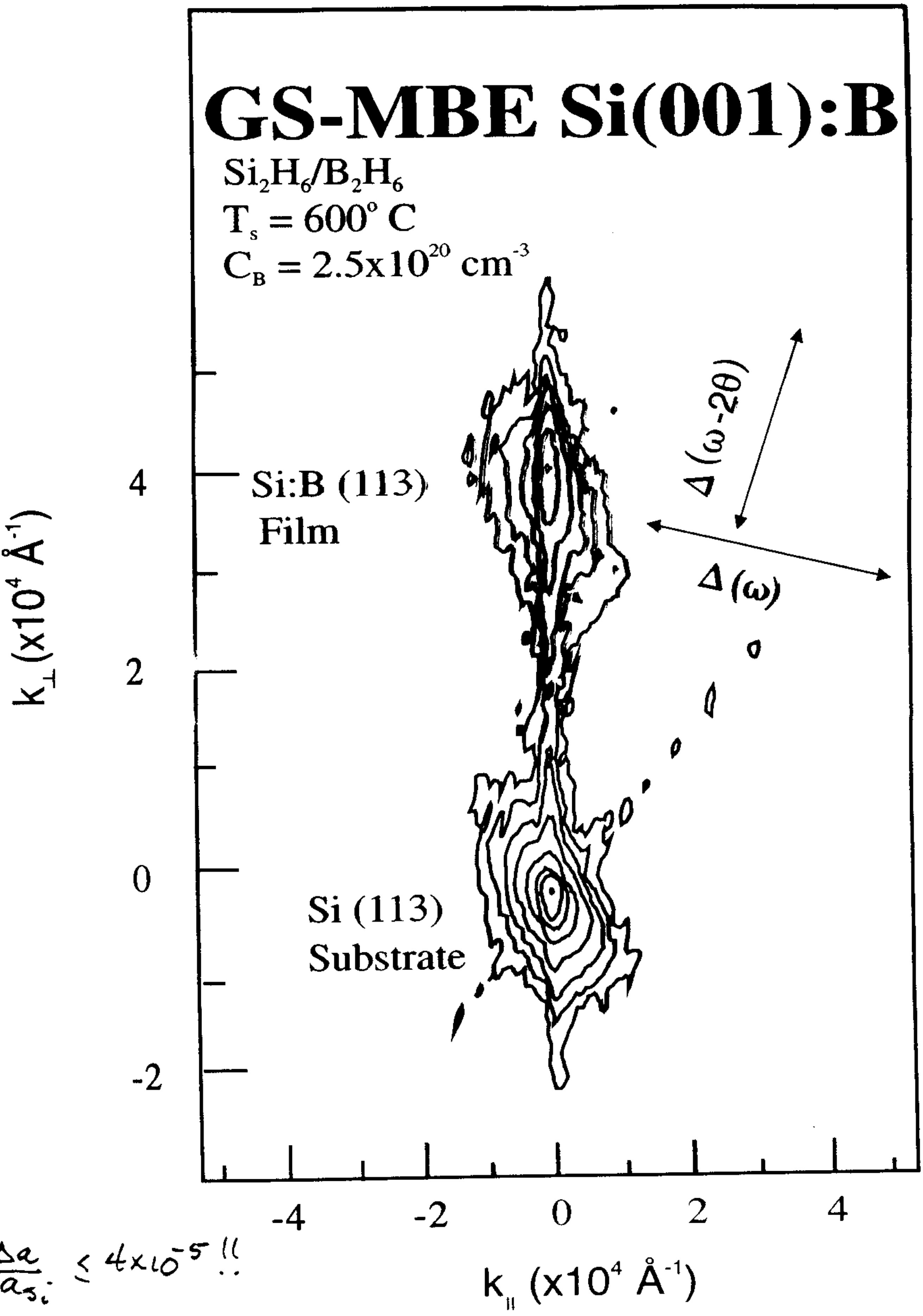


Lu, Bramblett, Lee, Hasan, Karasawa, Greene
J. Appl. Phys. 77, 3067 (1995)

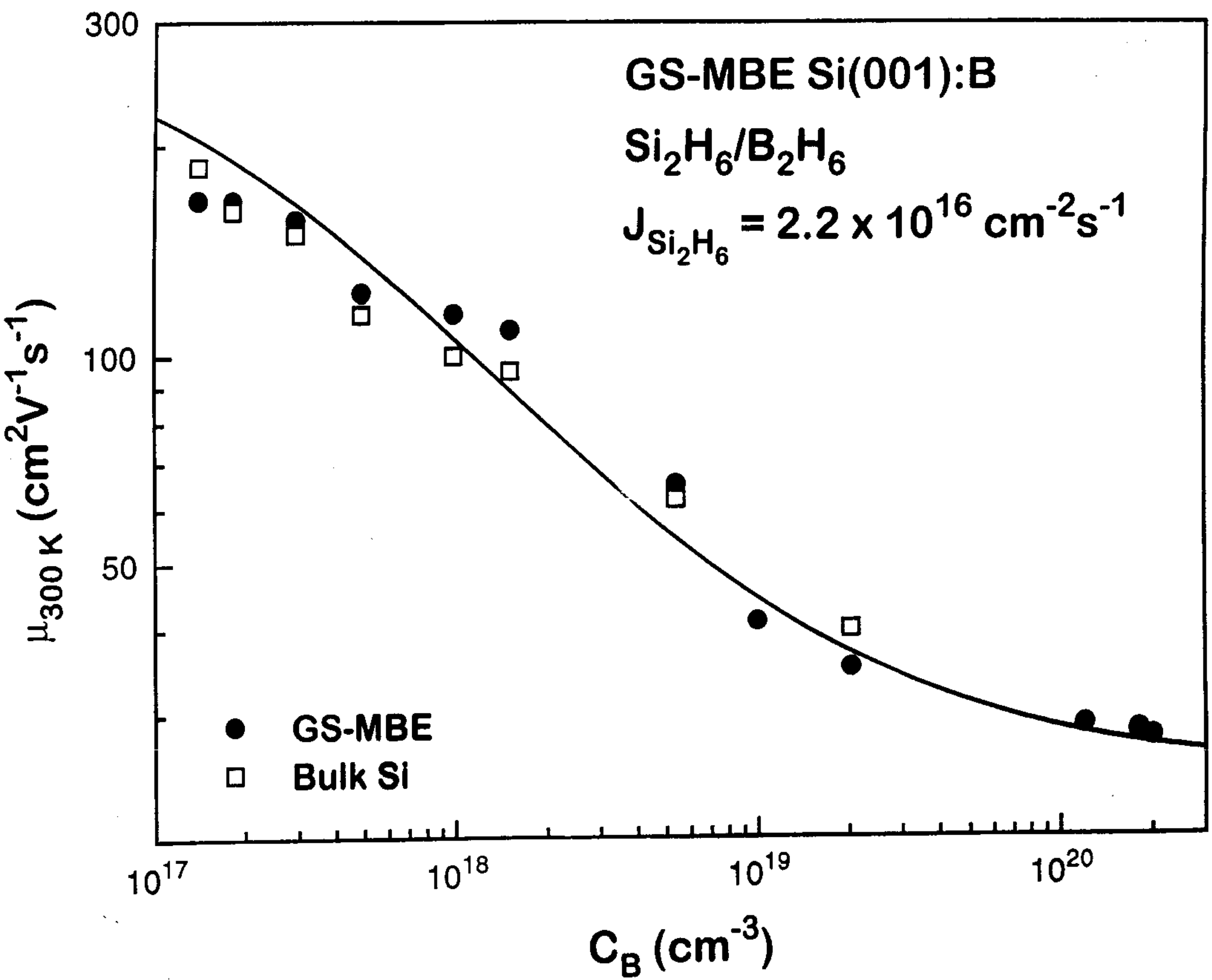

GS-MBE Si(001):B
Si_2H_6/B_2H_6
$J_{Si_2H_6} = 2.2 \times 10^{16}\ cm^{-2}s^{-1}$
T_s = 800 °C
T_s = 600 °C
$C_B\ (cm^{-3})$
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{-4}
10^{-3}
10^{-2}
0.1
$J_{B_2H_6}/J_{Si_2H_6}$

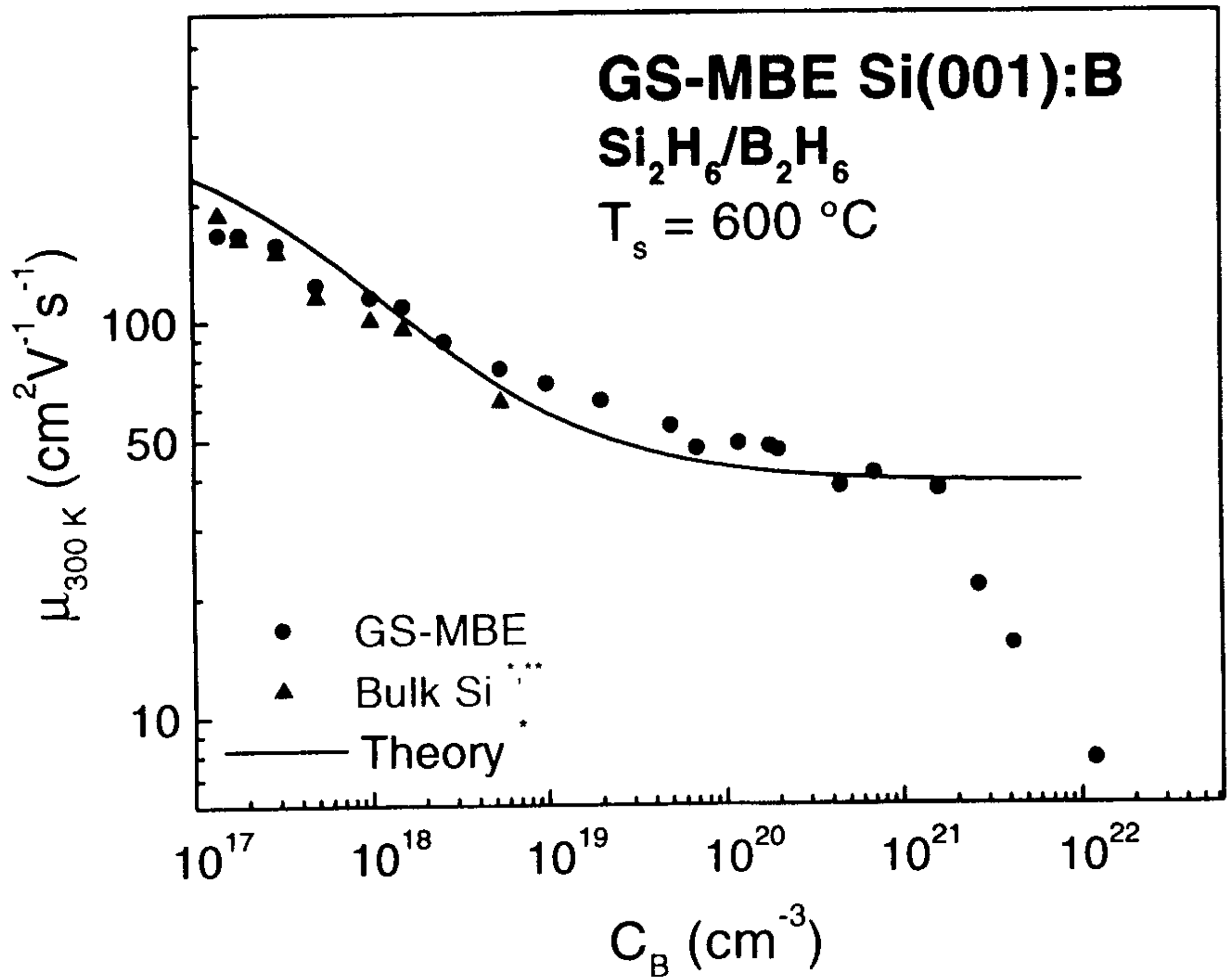

GS-MBE Si(001):B
Si2H6/B2H6
JSi2H6 = 2.2 x 10^16 cm^-2s^-1
NB (cm^-3)
B acceptor concn.
(Hall meas.)
10^17
10^18
10^19
10^20
CB (cm^-3)
Total B concn
(SIMS meas.)


GS-MBE Si(001):B
Si2H6/B2H6
JSi2H6 = 2.2 x 10^16 cm^-2s^-1
Ts = 550 °C
Ts = 600 °C
Ts = 800 °C
5.435
5.430
5.425
5.420
5.415
a⊥ (Å)
0
0.5
1.0
1.5
2.0
2.5
3.0
CB (10^20 cm^-3)



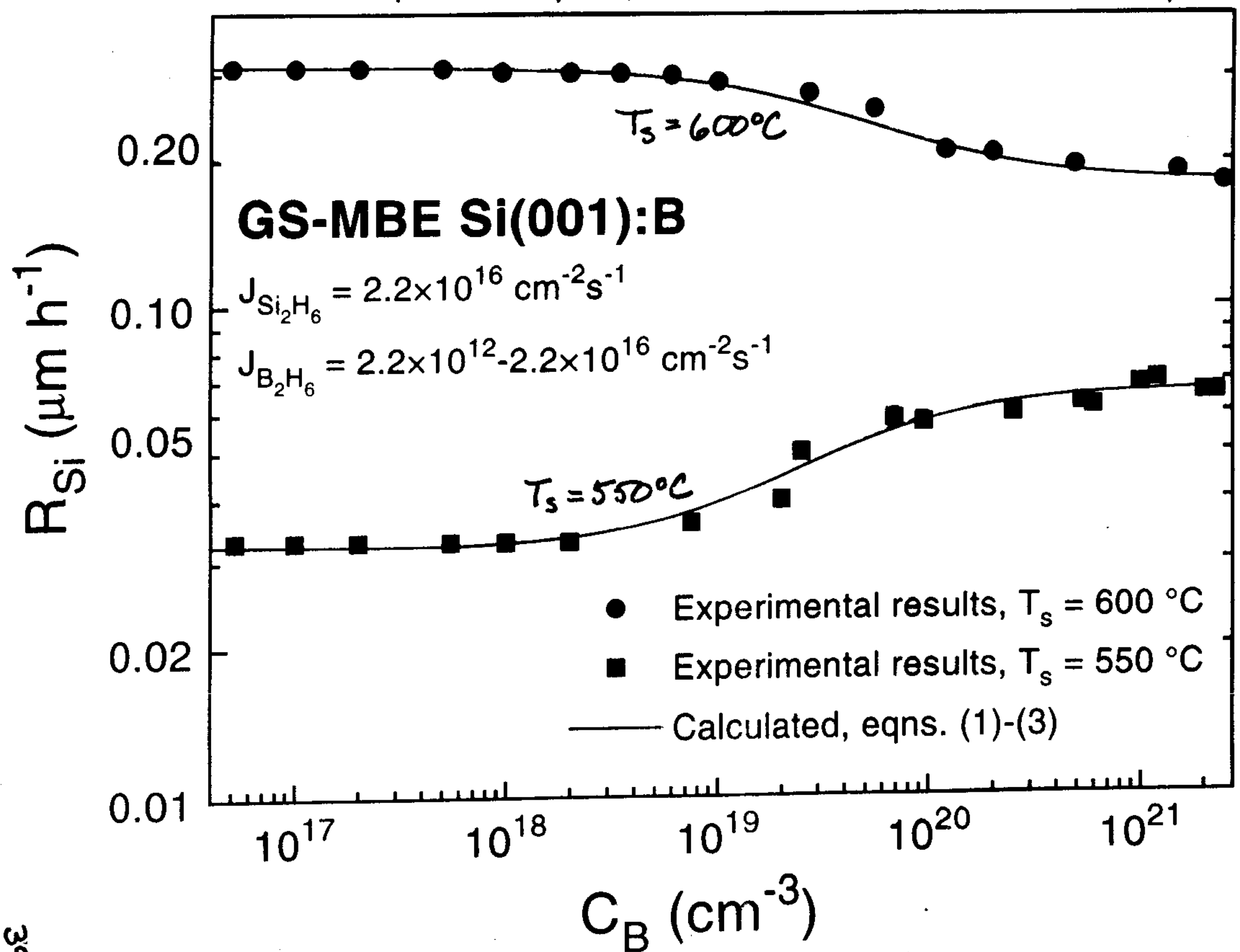
$\frac{\Delta a}{a_{Si}} \leq 4 \times 10^{-5}$!!

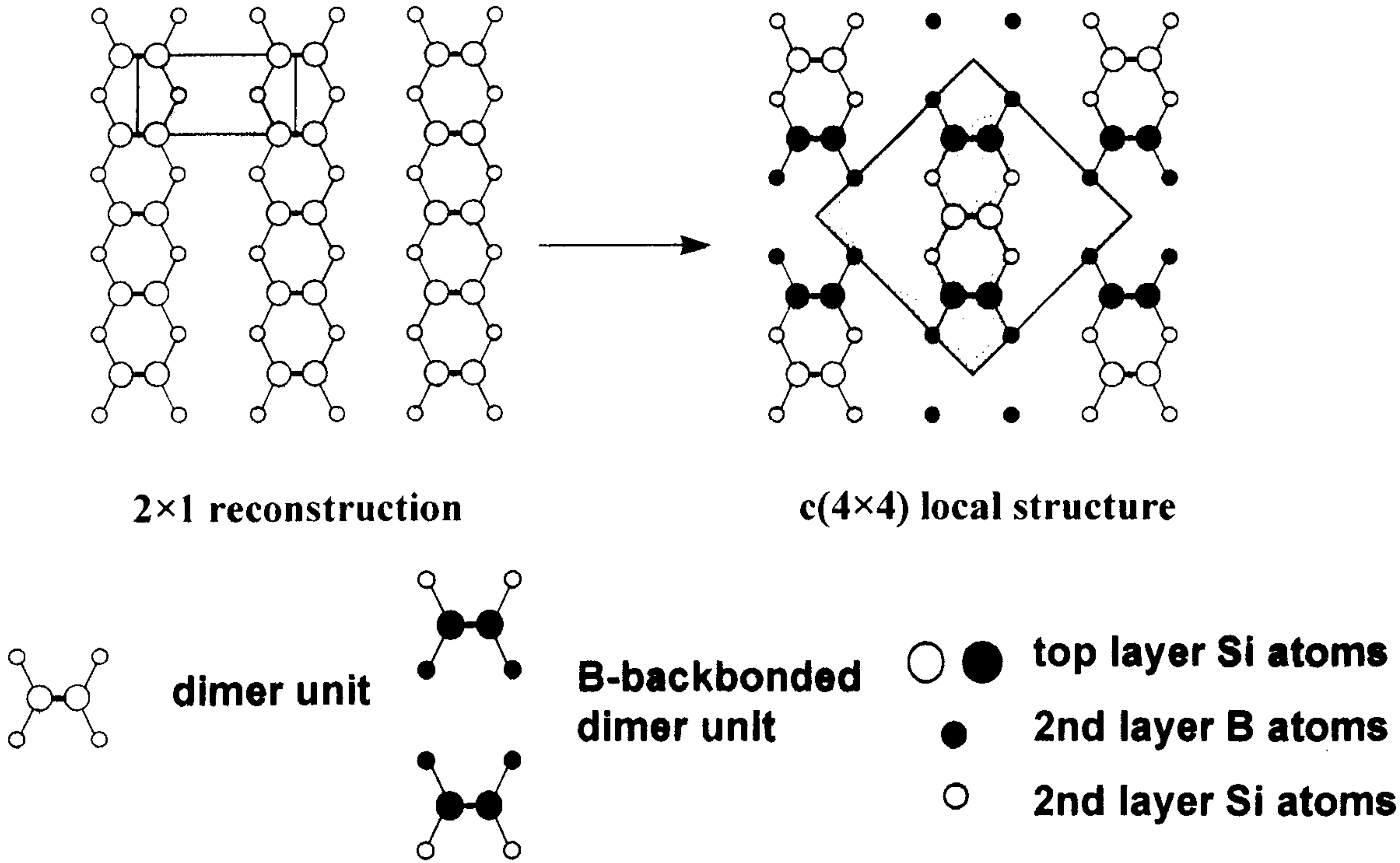

GS-MBE Si(001):B
Si_2H_6/B_2H_6
$J_{Si_2H_6} = 2.2 \times 10^{16}$ $cm^{-2}s^{-1}$
GS-MBE
Bulk Si
300
100
50
$\mu_{300 K}$ $(cm^2V^{-1}s^{-1})$
10^{17}
10^{18}
10^{19}
10^{20}
C_B (cm^{-3})



*D. Caughy, R. Thomas, Proc. IEEE **55** 2192 (1967).
G. A. Slack, and M. A. Hussain J. Appl. Phys., **70**, 2694 (1991).
S. Wagner, J. Electrochem. Soc. **119 1570 (1972).

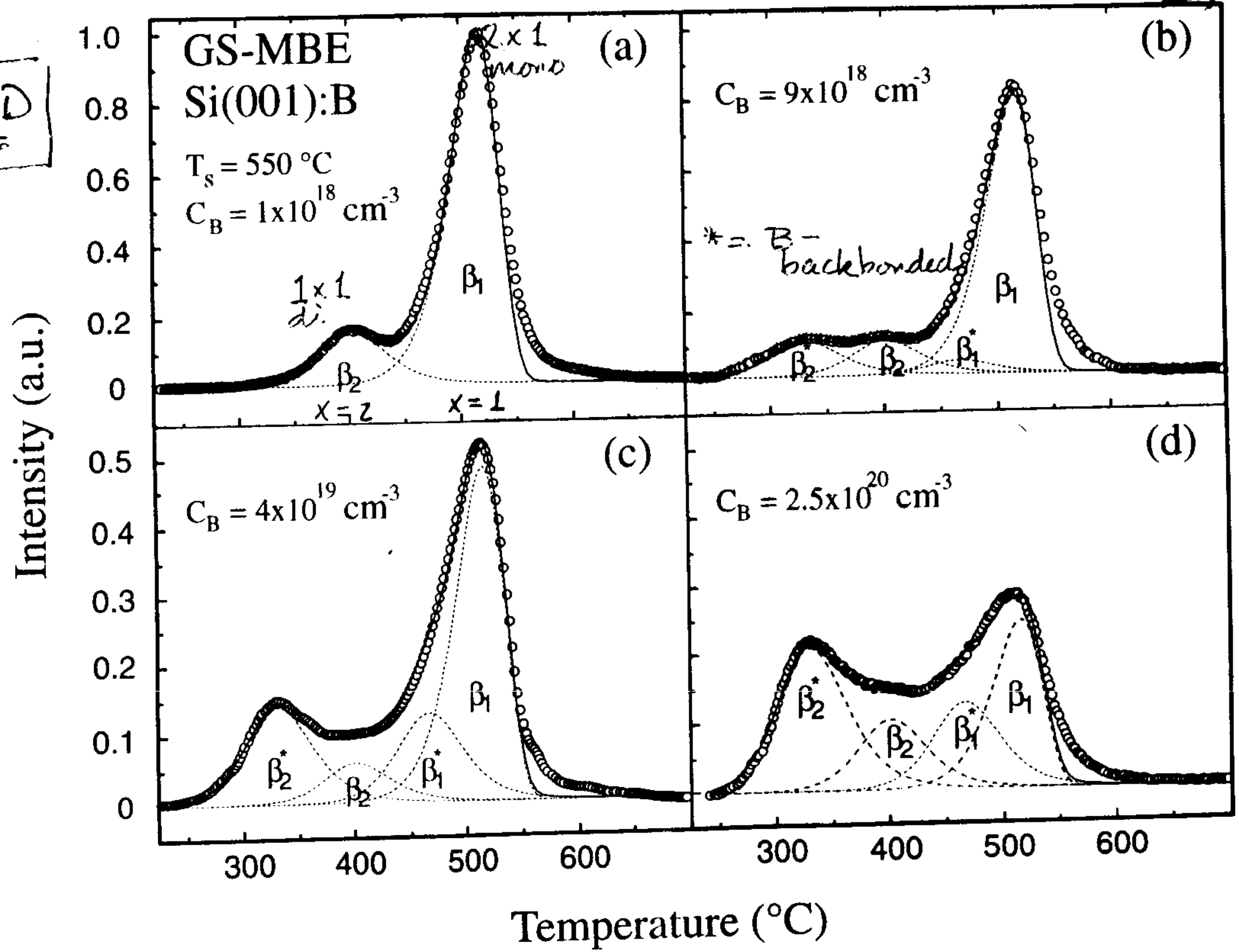
Glass, Kim, Sardela, Lu, Carlsson, Abelson, Greene, Surf. Sci. 392, 463 (1997).



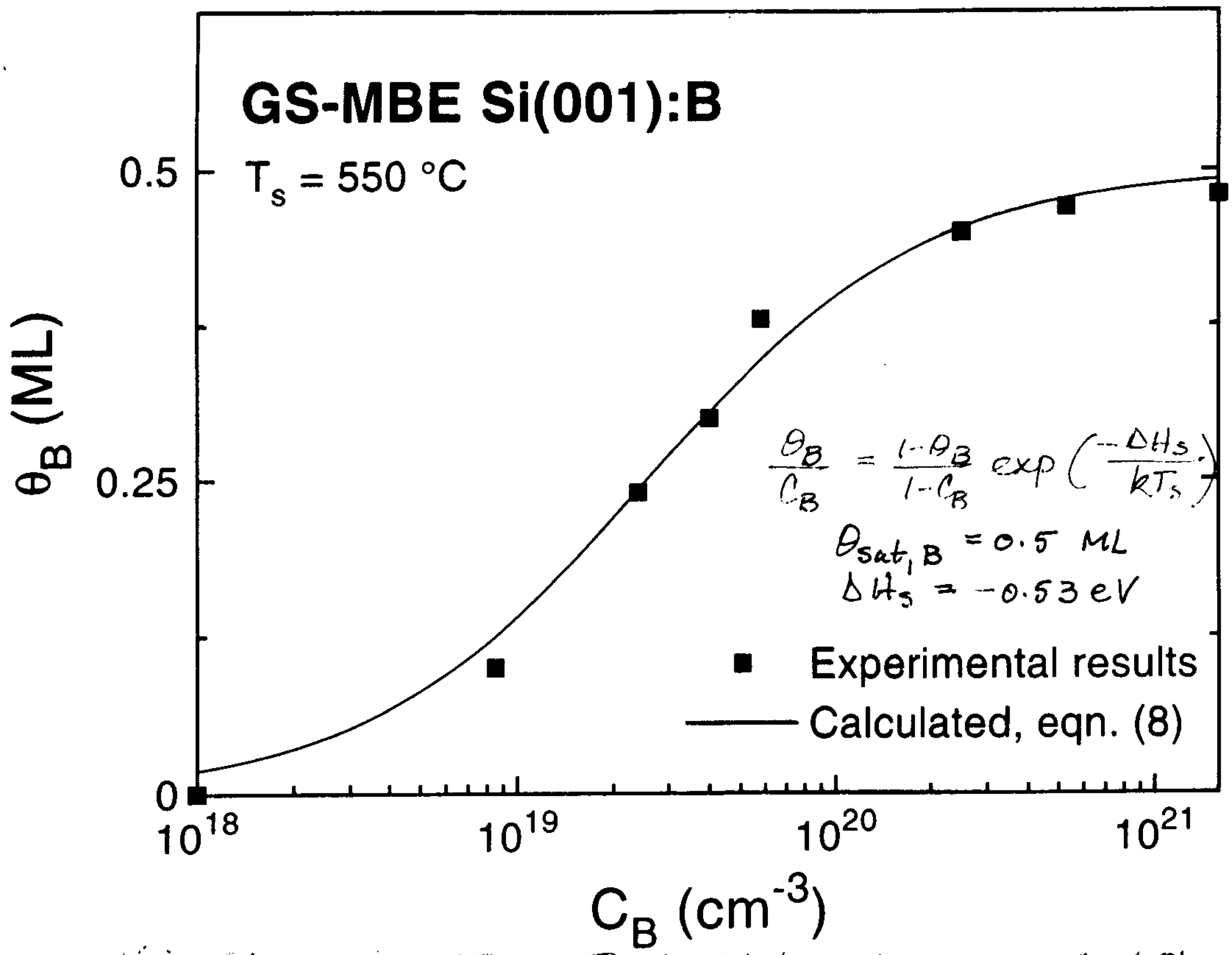

2×1 reconstruction
c(4×4) local structure
dimer unit
B-backbonded
dimer unit
top layer Si atoms
2nd layer B atoms
2nd layer Si atoms

D_2 TPD

Kim, Glass, Park, Spila, Taylor, Abelson, Greene, Appl. Phys. Lett. 69, 3869 ('96)

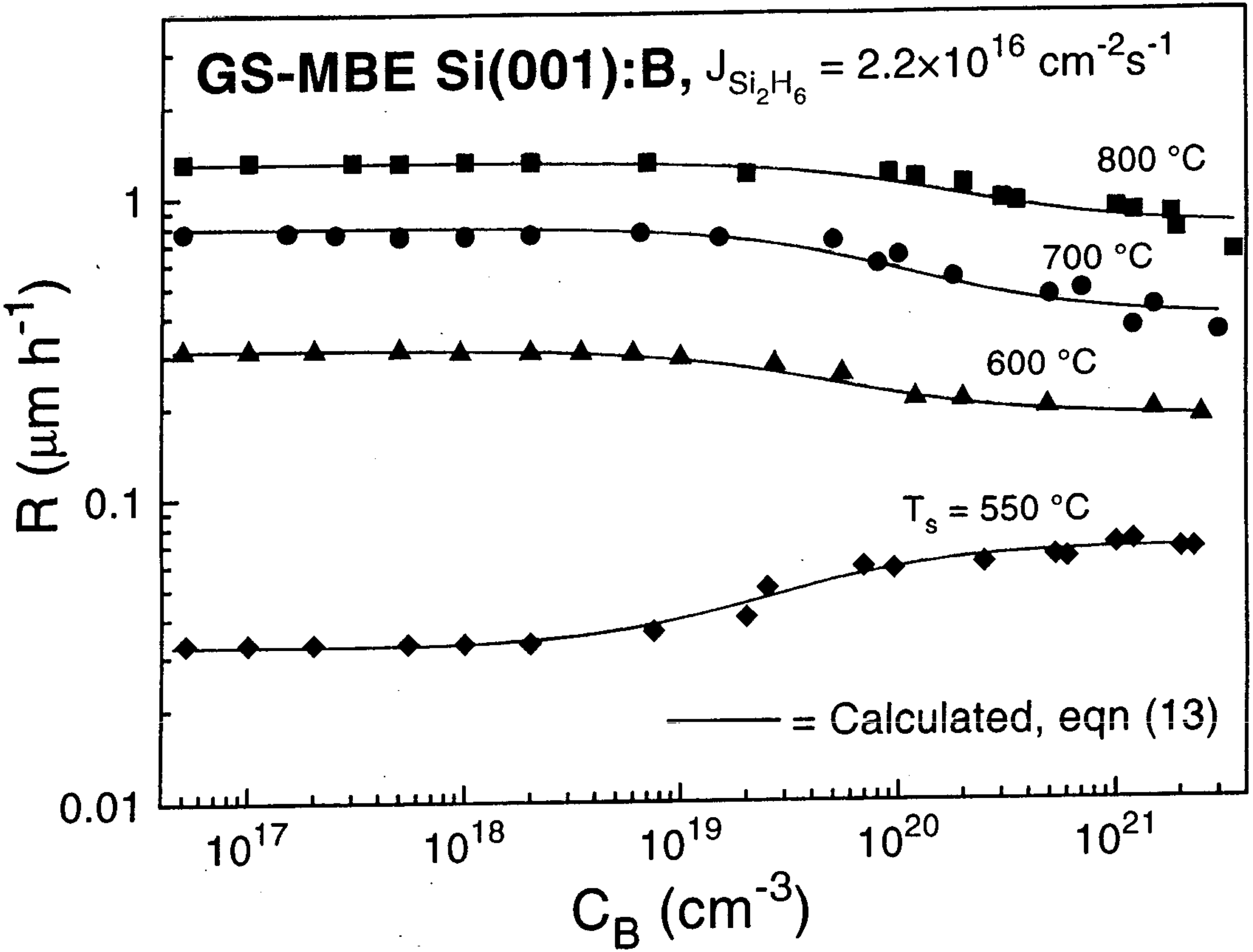


4



Kim, Glass, Spila, Taylor, Park, Abelson, Greene, J. Appl. Phys. [illegible]

$$R_{Si} = \frac{2 S_{Si_2H_6} J_{Si_2H_6}}{n_{Si}} \theta_{db}^2 \quad \text{where: } \theta_{db} = \text{fctn}(f, f^*, C_B, \theta_B)$$



GS-MBE/UHV-CVD Si(001):B

Growth Kinetics (Si_2H_6/B_2H_6)

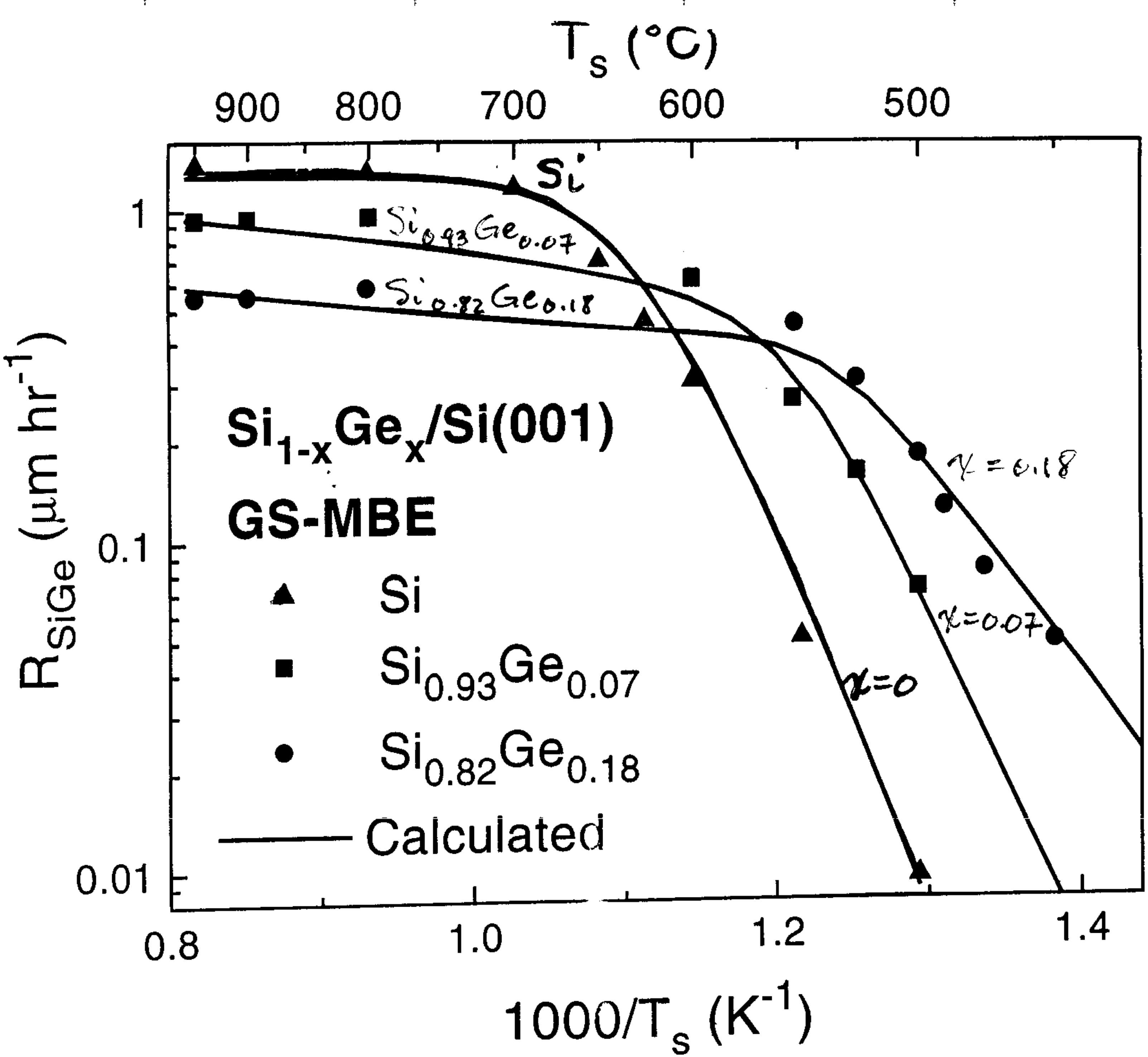
$$R_{Si} = \frac{2 J_{Si_2H_6} S_{Si_2H_6} \theta_{db}^2}{N_{Si}} ; \quad \boxed{R_{Si} \propto \theta_{db}^2}$$

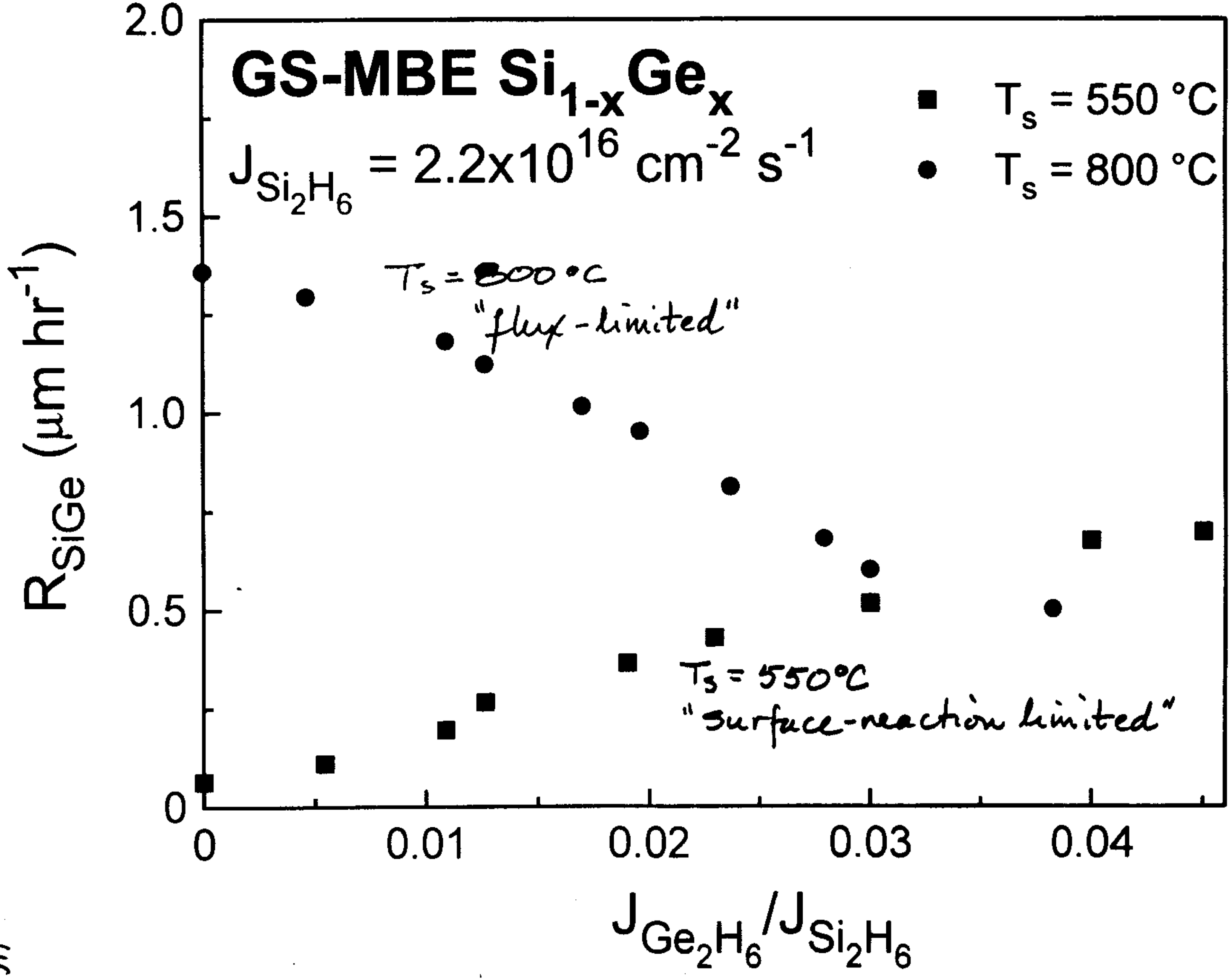
At $C_B \gtrsim 1 \times 10^{19}$ cm^{-3}:

- $\theta_{db} \downarrow$ due to
  - * Si dimer vacancies.
  - * deactivation of Si^*_{db} ($\simeq 1$ db/Si_2^*).
- But, $E_{d,H_2} \downarrow$ due to
  - * weakening of H-Si* bonds caused by Si*-B backbond charge transfer and increased strain.

Thus:

- In the flux-limited (hi T_s) growth mode
  - * $\theta_H \to 0$
  - * $\therefore R_{Si} \downarrow$ since $\theta_{db} \downarrow$
- In the surface-reaction (lo T_s) growth mode
  - * θ_H is large
  - * $\therefore R_{Si} \uparrow$ since net $\theta_{db} \uparrow$


T_s (°C)
900
800
700
600
500
R_{SiGe} (μm hr^{-1})
1
0.1
0.01
$Si_{1-x}Ge_x$/Si(001)
GS-MBE
Si
$Si_{0.93}Ge_{0.07}$
$Si_{0.82}Ge_{0.18}$
Calculated
0.8
1.0
1.2
1.4
1000/T_s (K^{-1})
Si
$Si_{0.93}Ge_{0.07}$
$Si_{0.82}Ge_{0.18}$
x=0.18
x=0.07
x=0



GS-MBE $Si_{1-x}Ge_x$
$J_{Si_2H_6} = 2.2x10^{16}\ cm^{-2}\ s^{-1}$
T_s = 550 °C
T_s = 800 °C
T_s = 800°C
"flux-limited"
T_s = 550°C
"surface-reaction limited"
2.0
1.5
1.0
0.5
0
R_{SiGe} (μm hr^{-1})
0
0.01
0.02
0.03
0.04
$J_{Ge_2H_6}/J_{Si_2H_6}$

Calculating gas-source $Si_{1-x}Ge_x$ growth rates requires:

$S_{Si_2H_6}(\theta_{Ge}, T_s)$
$S_{Ge_2H_6}(\theta_{Ge}, T_s)$ } $S^{Si}_{Si_2H_6}$, $S^{Ge}_{Si_2H_6}$; $S^{Si}_{Ge_2H_6}$, $S^{Ge}_{Ge_2H_6}$

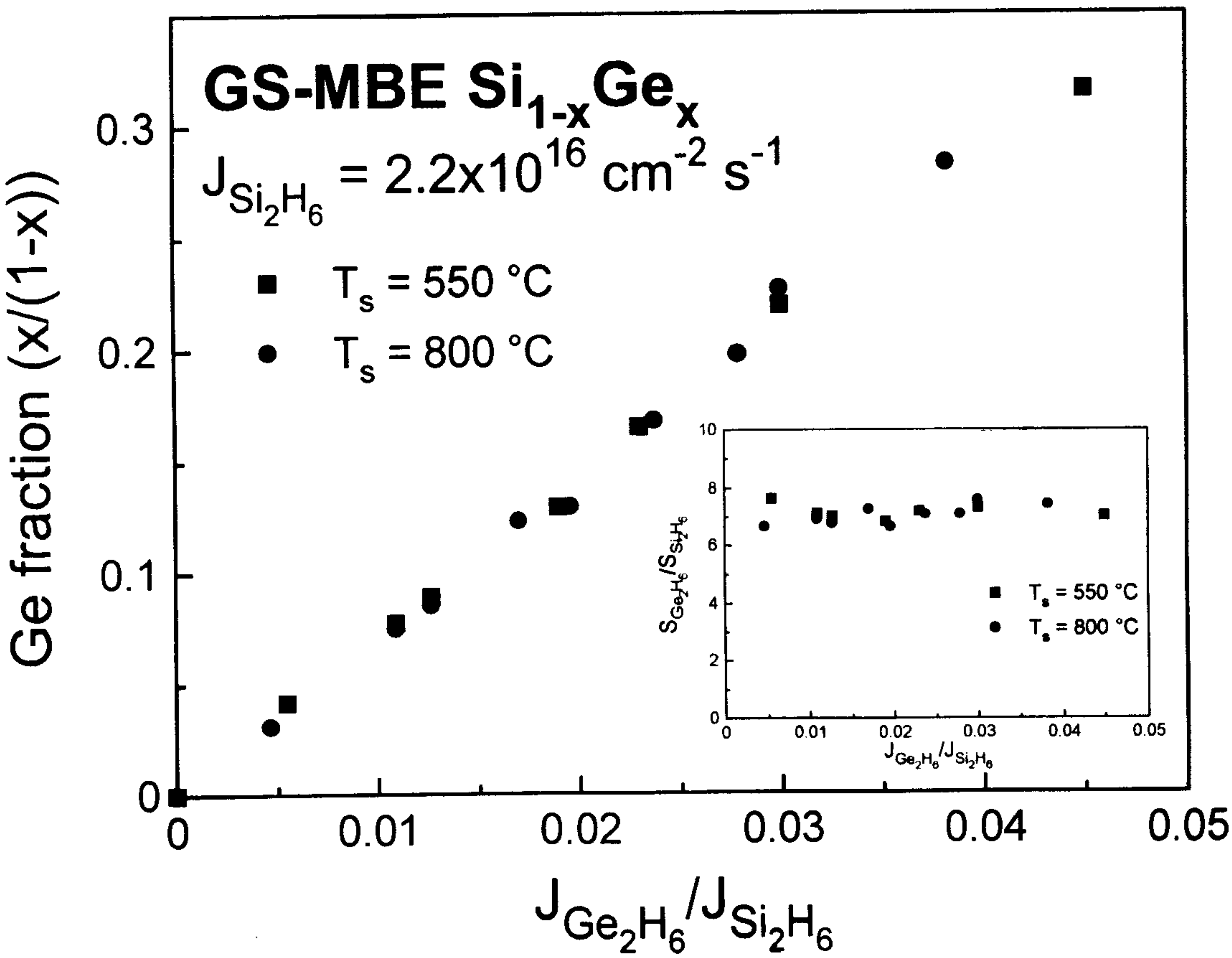
$\theta_{Ge}(x, T_s)$
$\theta_H(x, T_s)$ 〉 $\Delta H_{s,Ge}[\theta_H(x, T_s)]$

$E^H_{Si}(\theta_{Ge})$
$E^H_{Ge}(\theta_{Ge})$

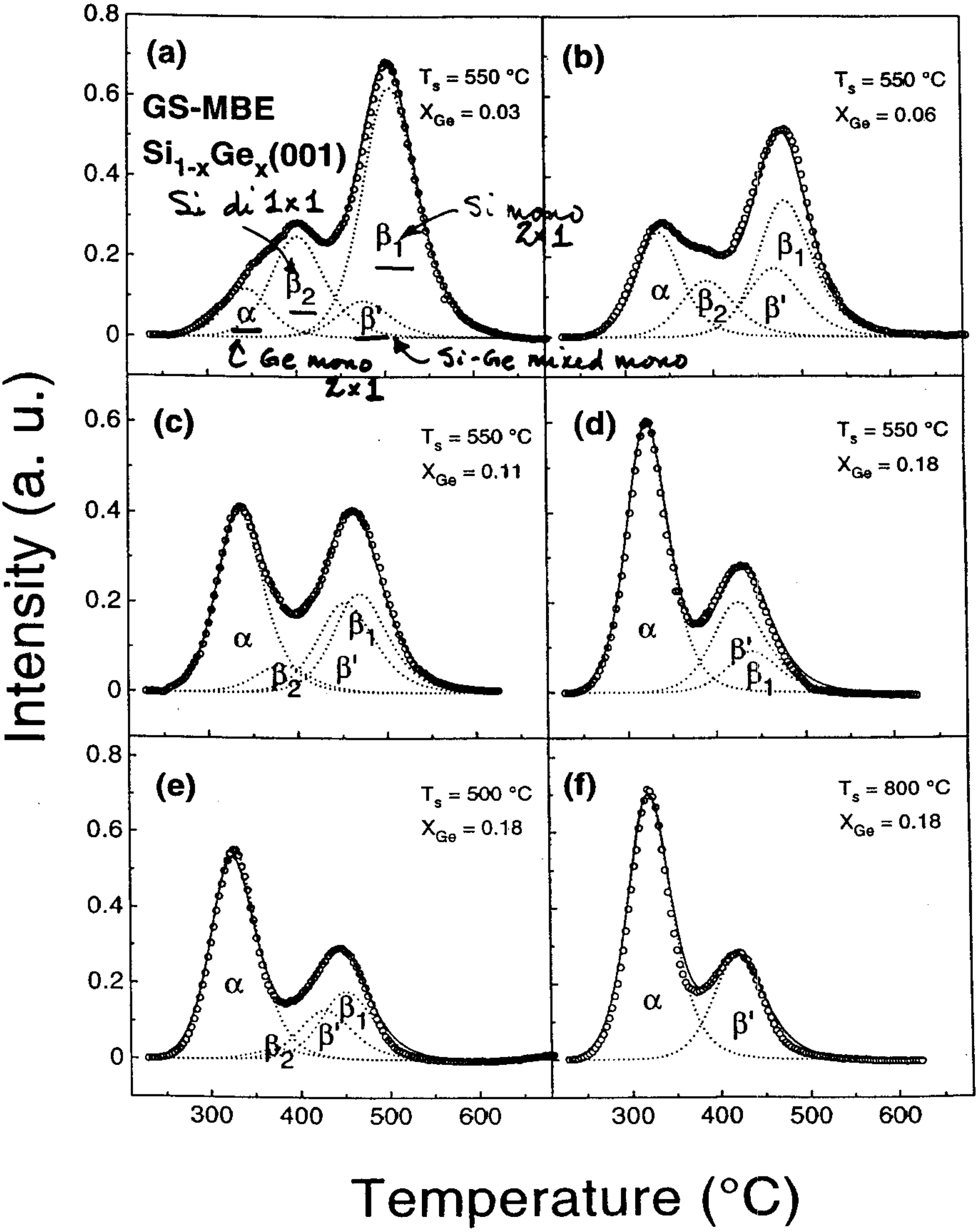
$f_{Si,db}(x, \theta_{Ge}, T_s)$
$f_{Ge,db}(x, \theta_{Ge}, T_s)$

Knowledge of H desorption pathway from SiGe

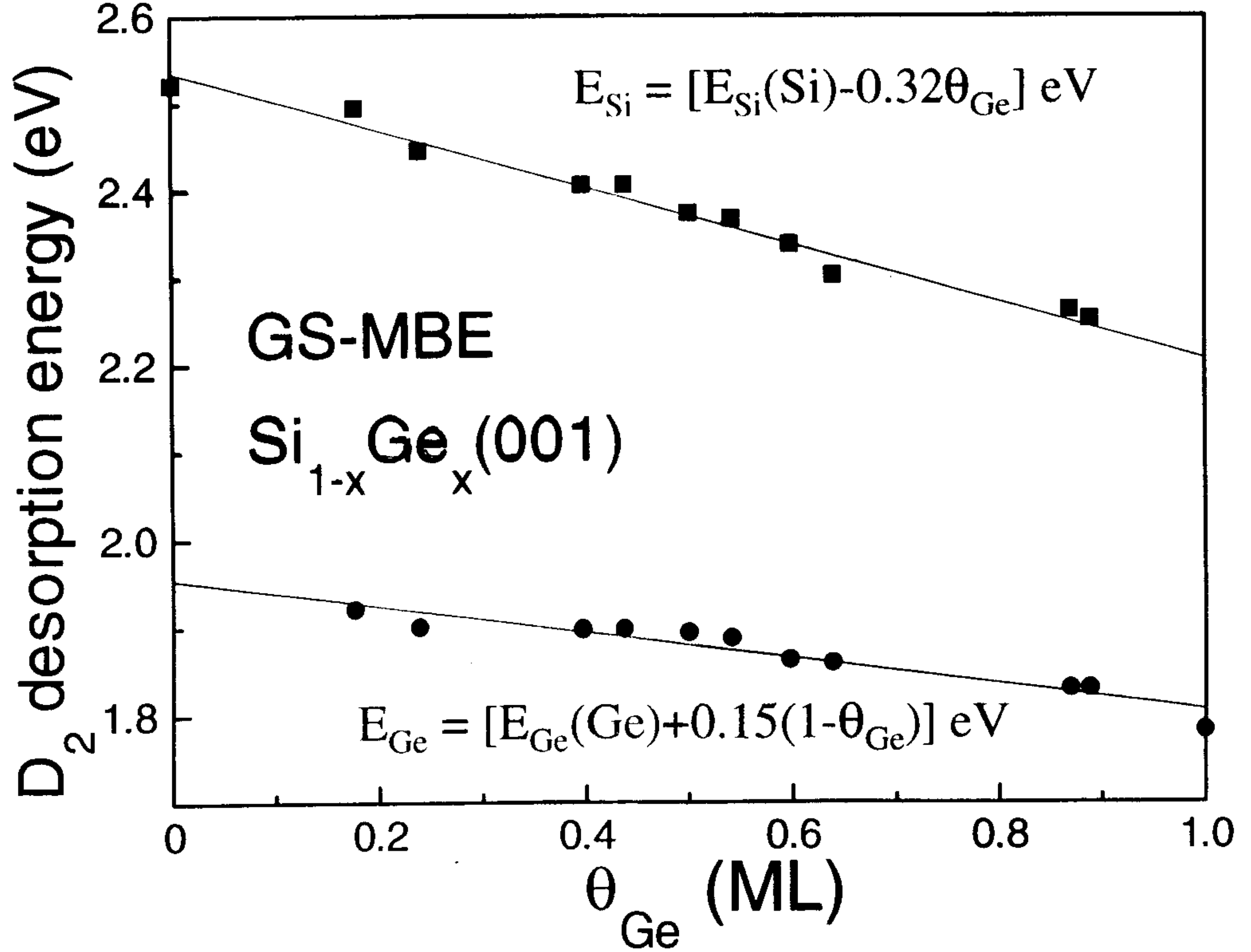
Kinetic order of all adsorption, surface decomposition, and desorption steps

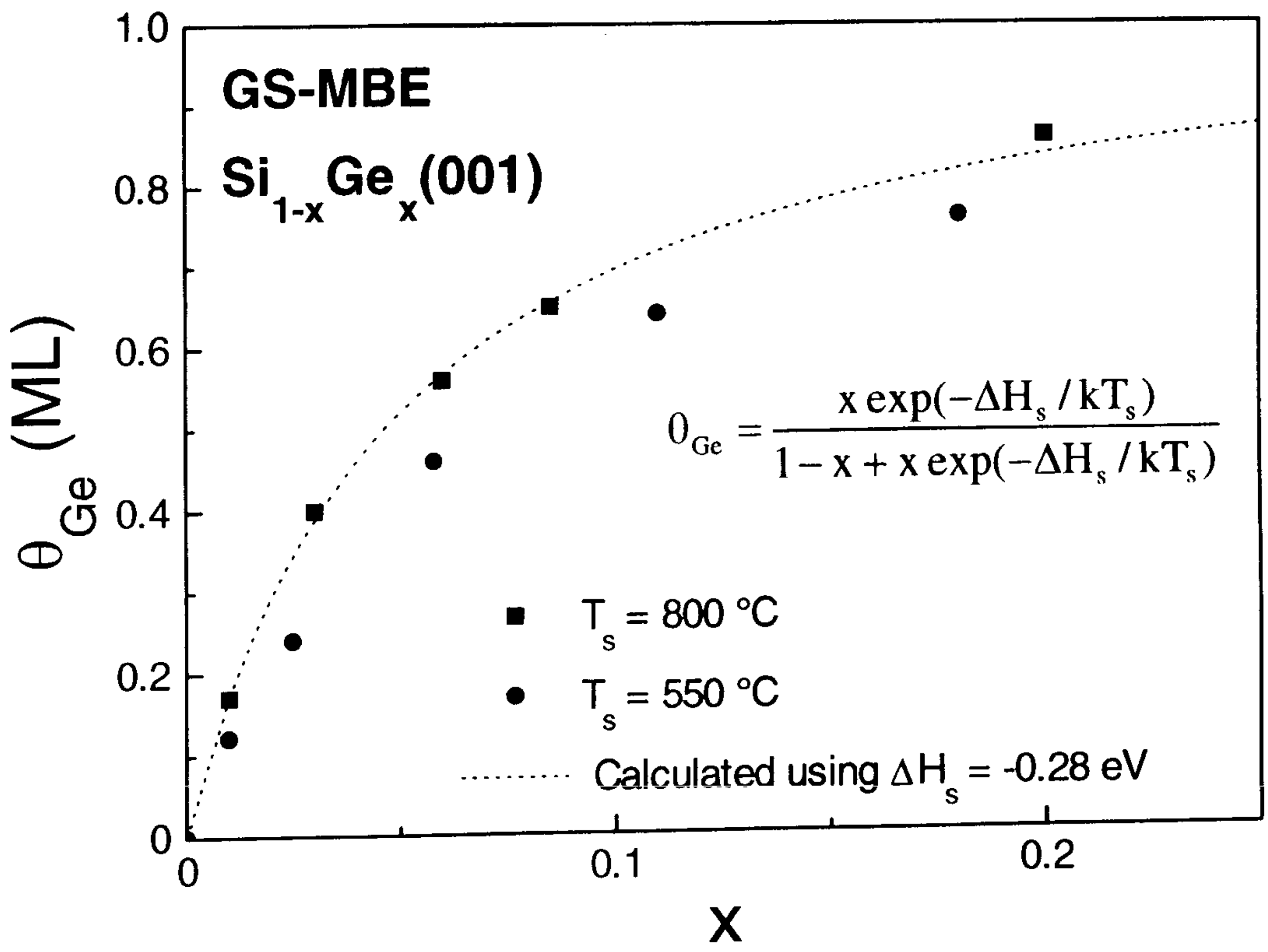

GS-MBE $Si_{1-x}Ge_x$
$J_{Si_2H_6} = 2.2x10^{16}\ cm^{-2}\ s^{-1}$
T_s = 550 °C
T_s = 800 °C
Ge fraction (x/(1-x))
0.3
0.2
0.1
0
0
0.01
0.02
0.03
0.04
0.05
$J_{Ge_2H_6}/J_{Si_2H_6}$
$S_{Ge_2H_6}/S_{Si_2H_6}$
10
8
6
4
2
0
0
0.01
0.02
0.03
0.04
0.05
$J_{Ge_2H_6}/J_{Si_2H_6}$
T_s = 550 °C
T_s = 800 °C

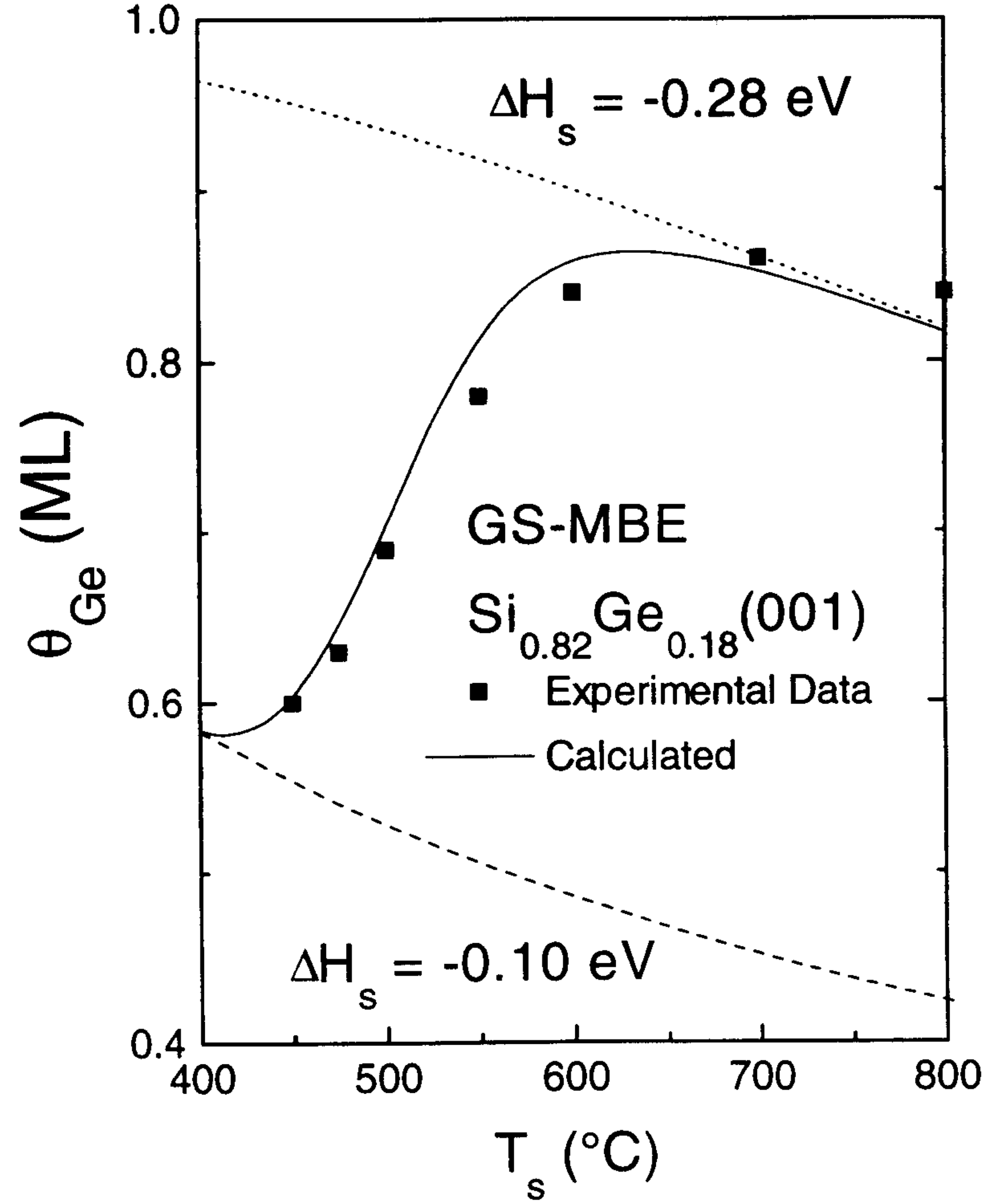
β_1 = Si monodeuteride, 2×1 β' = Ge-Si monodeuteride
β_2 = Si dideuteride, 1×1 α = Ge monodeuteride



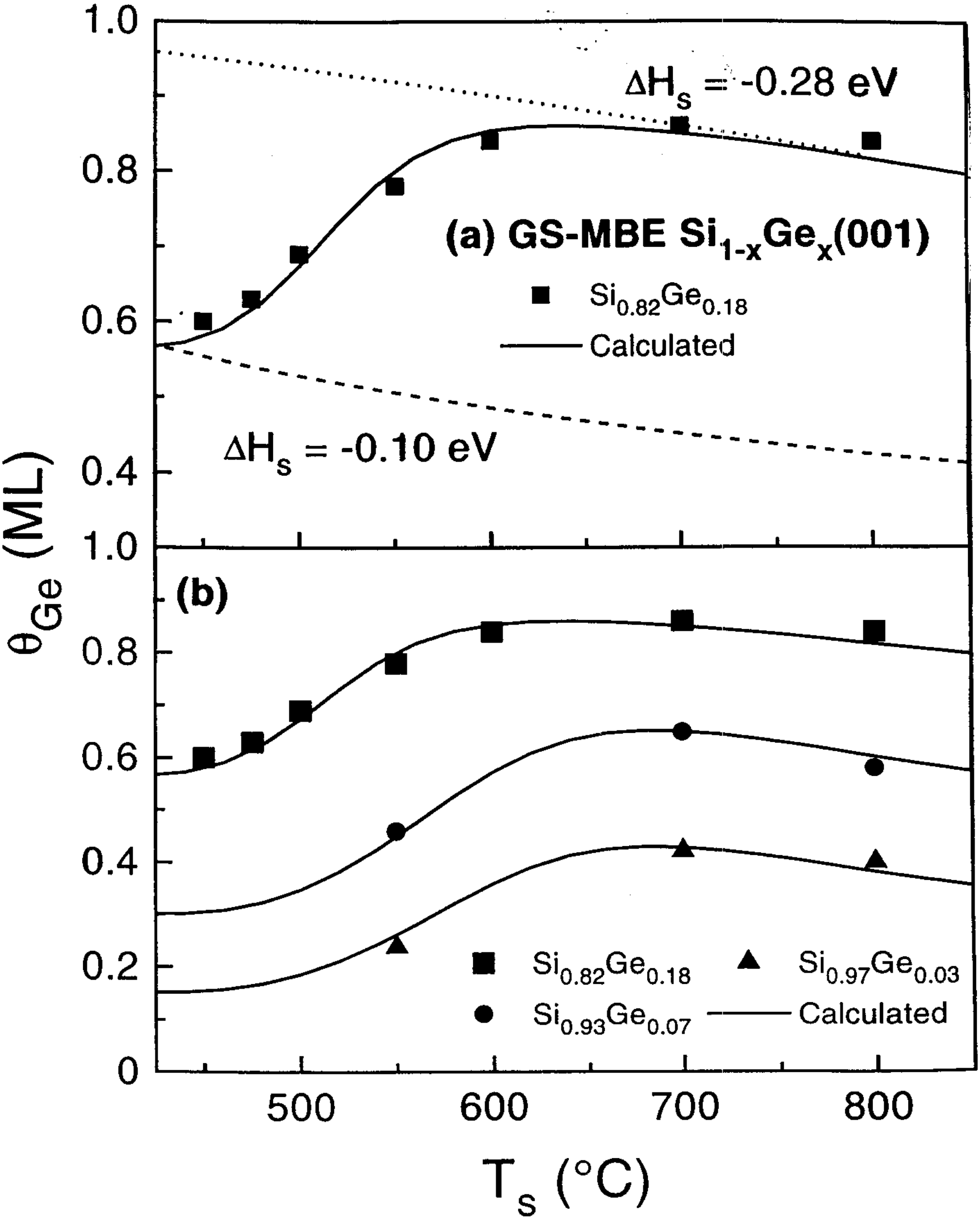
$I_{\beta_1} + I_{\beta_1'} + I_{\alpha}$ = constant ⇒ n_{Si} (i.e. fully-strained)


2.6
2.4
2.2
2.0
1.8
D2 desorption energy (eV)
E_Si = [E_Si(Si)-0.32θ_Ge] eV
GS-MBE
Si1-xGex(001)
E_Ge = [E_Ge(Ge)+0.15(1-θ_Ge)] eV
0
0.2
0.4
0.6
0.8
1.0
θGe (ML)


GS-MBE
Si1-xGex(001)
θGe (ML)
x
1.0
0.8
0.6
0.4
0.2
0
0.1
0.2
θGe = x exp(−ΔHs / kTs) / (1 − x + x exp(−ΔHs / kTs))
Ts = 800 °C
Ts = 550 °C
Calculated using ΔHs = -0.28 eV



1.0
0.8
0.6
0.4
400
500
600
700
800
ΔH s = -0.28 eV
ΔH s = -0.10 eV
GS-MBE
Si 0.82 Ge 0.18 (001)
Experimental Data
Calculated
θ Ge (ML)
T s (°C)



1.0
0.8
0.6
0.4
ΔH_s = -0.28 eV
(a) GS-MBE $Si_{1-x}Ge_x(001)$
$Si_{0.82}Ge_{0.18}$
Calculated
ΔH_s = -0.10 eV
θ_{Ge} (ML)
1.0
(b)
0.8
0.6
0.4
0.2
0
$Si_{0.82}Ge_{0.18}$
$Si_{0.97}Ge_{0.03}$
$Si_{0.93}Ge_{0.07}$
Calculated
500
600
700
800
T_s (°C)

Gas-source $Si_{1-x}Ge_x$ growth rate

$$R_{SiGe} = \frac{2\theta_{Si} f^2_{db,Si}}{N_{SiGe}}\left(J_{Si_2H_6} S^{Si}_{Si_2H_6} + J_{Ge_2H_6} S^{Si}_{Ge_2H_6}\right) + \frac{2\theta_{Ge} f^2_{db,Ge}}{N_{SiGe}}\left(J_{Si_2H_6} S^{Ge}_{Si_2H_6} + J_{Ge_2H_6} S^{Ge}_{Ge_2H_6}\right)$$

$$\theta_{Ge} = f_{Si,db}\left(\frac{x \exp(-\Delta H^1_s/kT_s)}{1-x+x\exp(-\Delta H^1_s/kT_s)}\right) + (1-f_{Si,db})\left(\frac{x\exp(-\Delta H^2_s/kT_s)}{1-x+x\exp(-\Delta H^2_s/kT_s)}\right)$$

where: $\Delta H^1_s = -0.28$ eV, $\Delta H^2_s = -0.10$ eV

$$\theta_{Ge} + \theta_{Si} = 1$$

$$f_{Si,db} = \left[1 + \frac{\sqrt{2 J_{Si_2H_6} S_{Si_2H_6}}}{N_{SiGe} \nu_s \exp(-E^H_{Si}/kT_s)}\right]$$

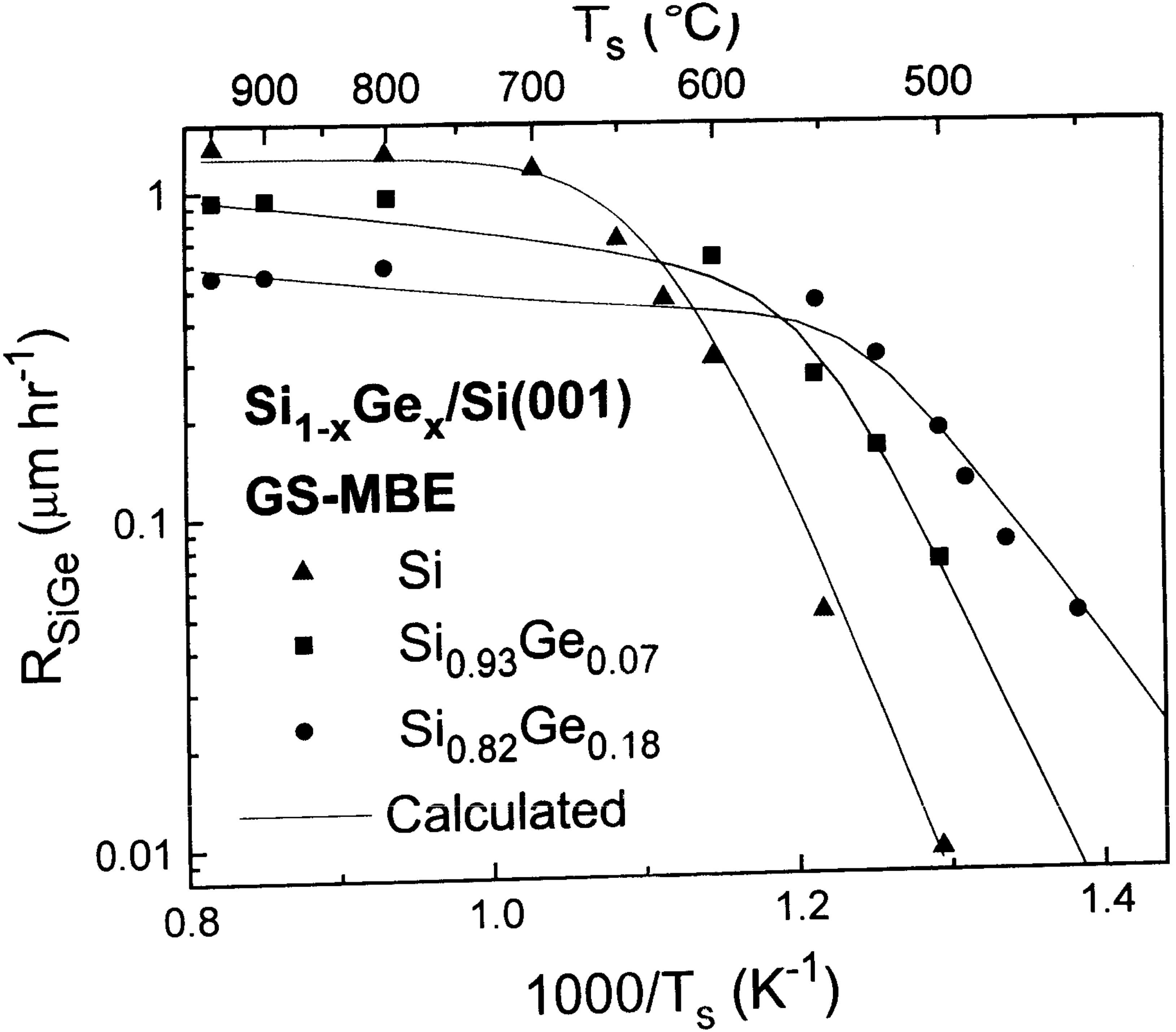
$$f_{Ge,db} = \left[1 + \frac{\sqrt{2 J_{Ge_2H_6} S_{Ge_2H_6}}}{N_{SiGe} \nu_s \exp(-E^H_{Ge}/kT_s)}\right]$$

$$\bar{E}^H_{Si} = [2.52 - 0.32\,\theta_{Ge}]$$

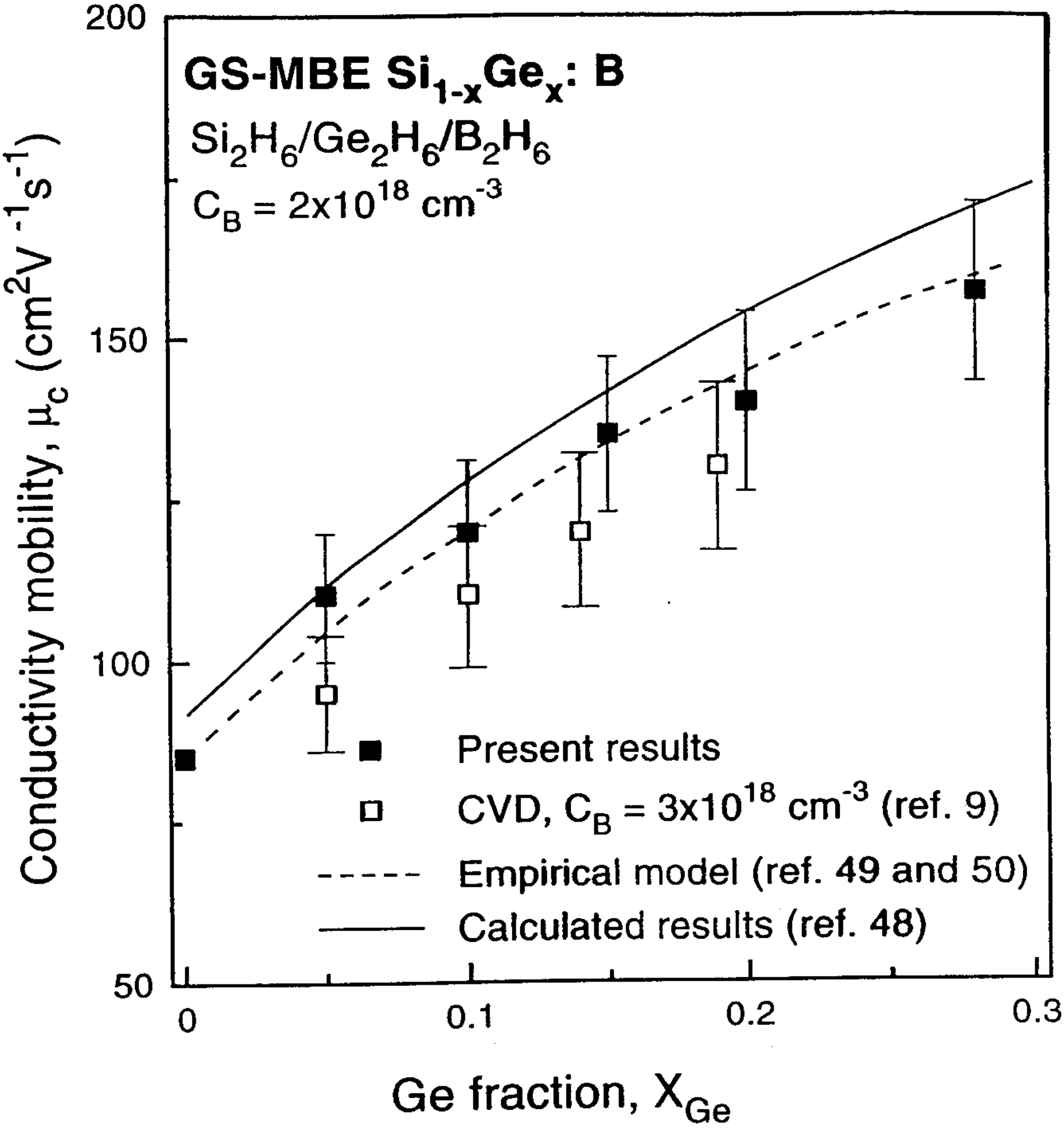
$$\bar{E}^H_{Ge} = [1.80 + 0.15\,(1-\theta_{Ge})]$$

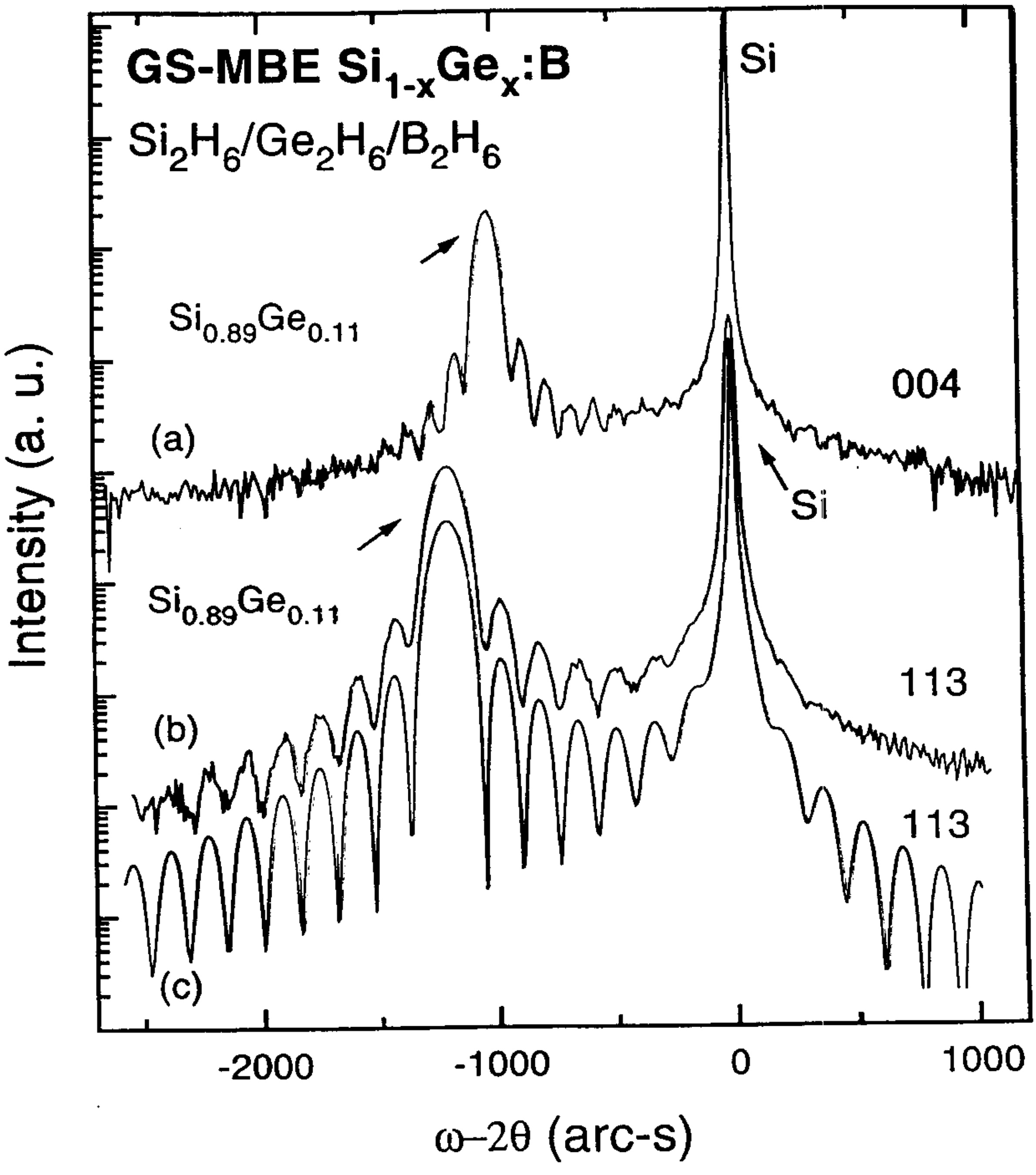
$$S_{Si_2H_6} = \theta_{Si} S^{Si}_{Si_2H_6} + \theta_{Ge} S^{Ge}_{Si_2H_6}$$

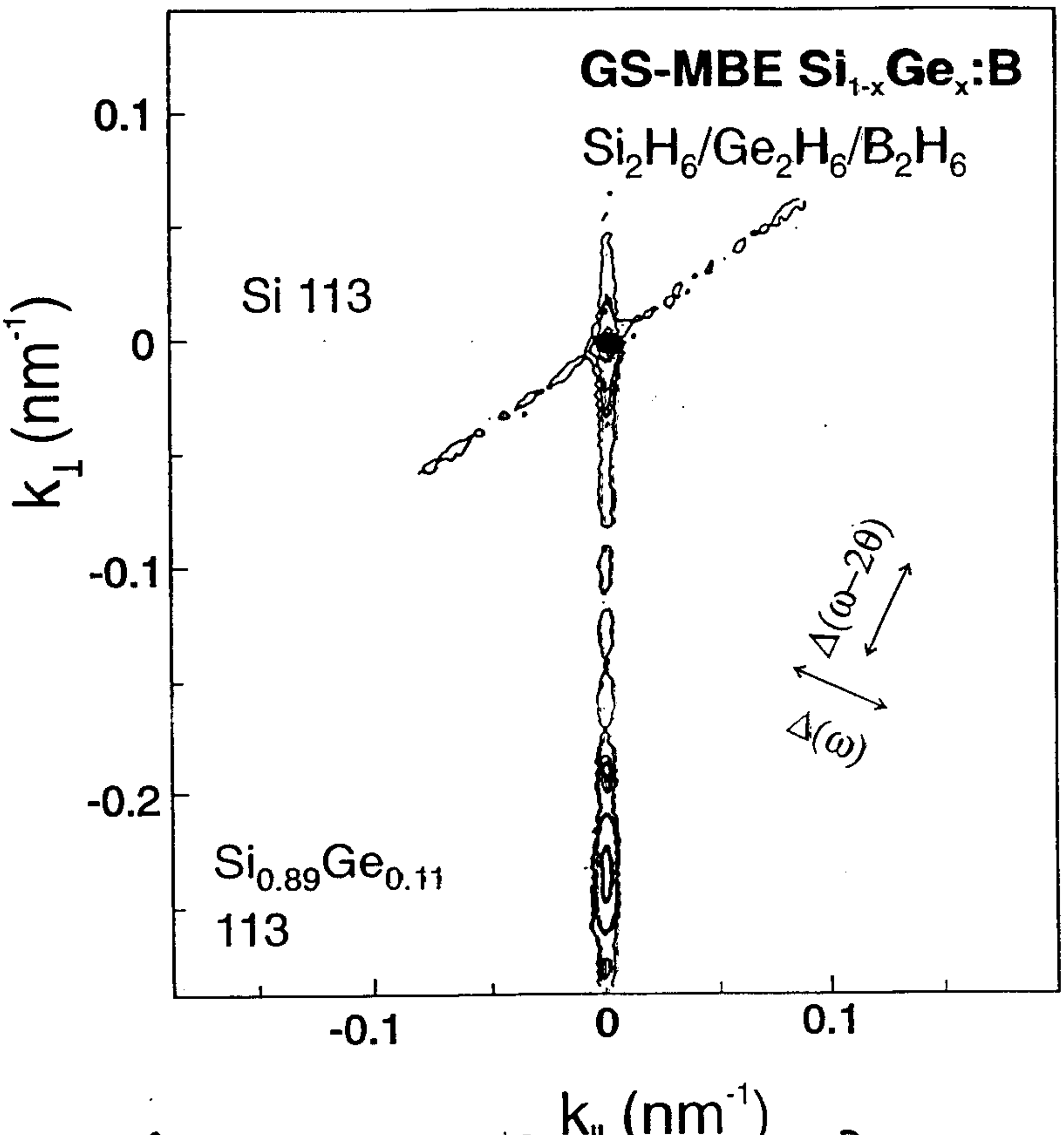
$$S_{Ge_2H_6} = \theta_{Ge} S^{Ge}_{Ge_2H_6} + \theta_{Si} S^{Si}_{Ge_2H_6}$$



T_s (°C)
900
800
700
600
500
R_{SiGe} (μm hr^{-1})
1
0.1
0.01
$Si_{1-x}Ge_x/Si(001)$
GS-MBE
Si
$Si_{0.93}Ge_{0.07}$
$Si_{0.82}Ge_{0.18}$
Calculated
0.8
1.0
1.2
1.4
1000/T_s (K^{-1})


GS-MBE $Si_{1-x}Ge_x$: B
$Si_2H_6/Ge_2H_6/B_2H_6$
$C_B = 2x10^{18}$ cm^{-3}
Present results
CVD, $C_B = 3x10^{18}$ cm^{-3} (ref. 9)
Empirical model (ref. 49 and 50)
Calculated results (ref. 48)
Conductivity mobility, μ_c ($cm^2V^{-1}s^{-1}$)
Ge fraction, X_{Ge}
200
150
100
50
0
0.1
0.2
0.3

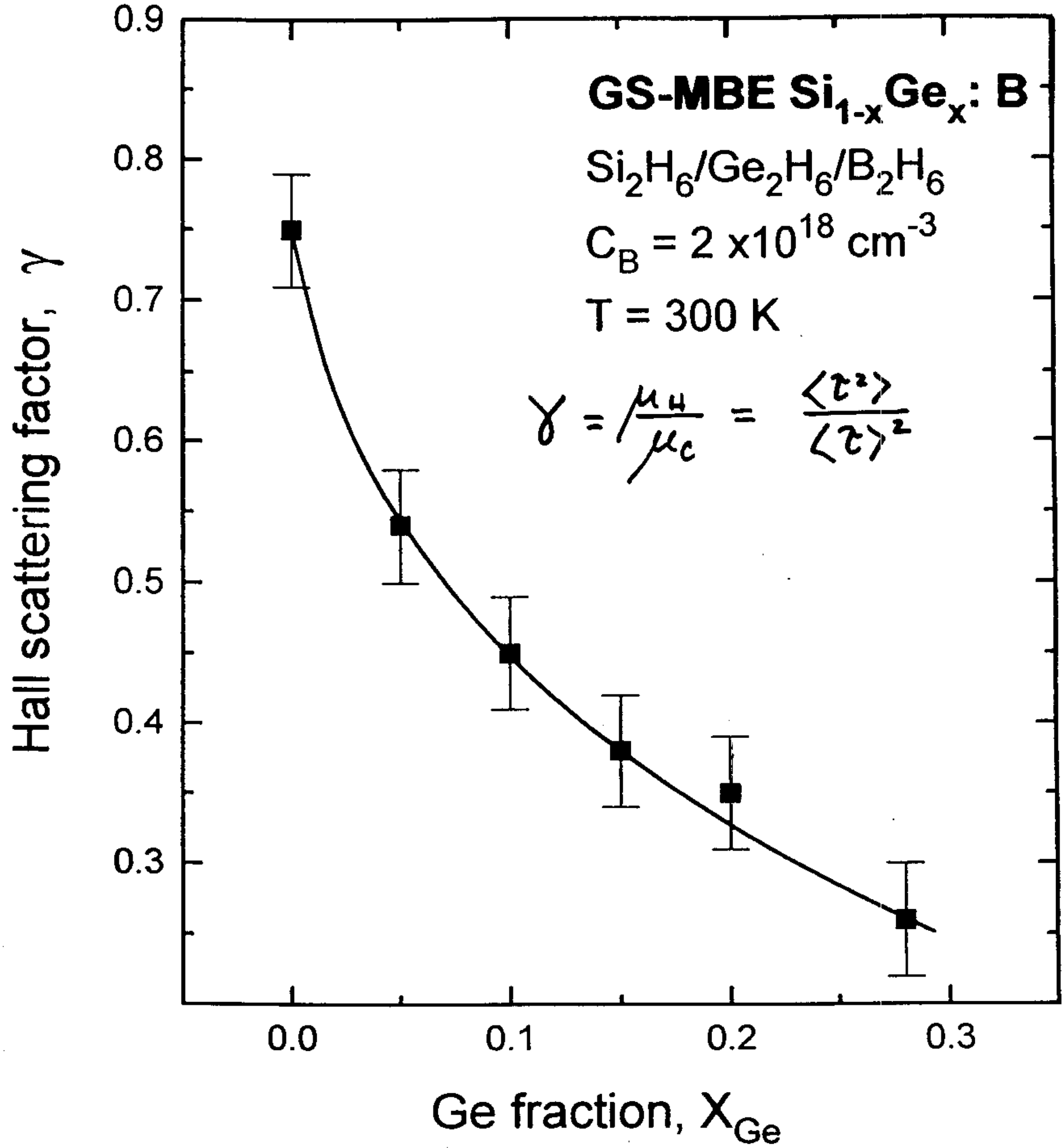

GS-MBE Si1-xGex:B
Si2H6/Ge2H6/B2H6
Si
Si0.89Ge0.11
(a)
004
Si
Si0.89Ge0.11
(b)
113
113
(c)
Intensity (a. u.)
-2000
-1000
0
1000
ω–2θ (arc-s)



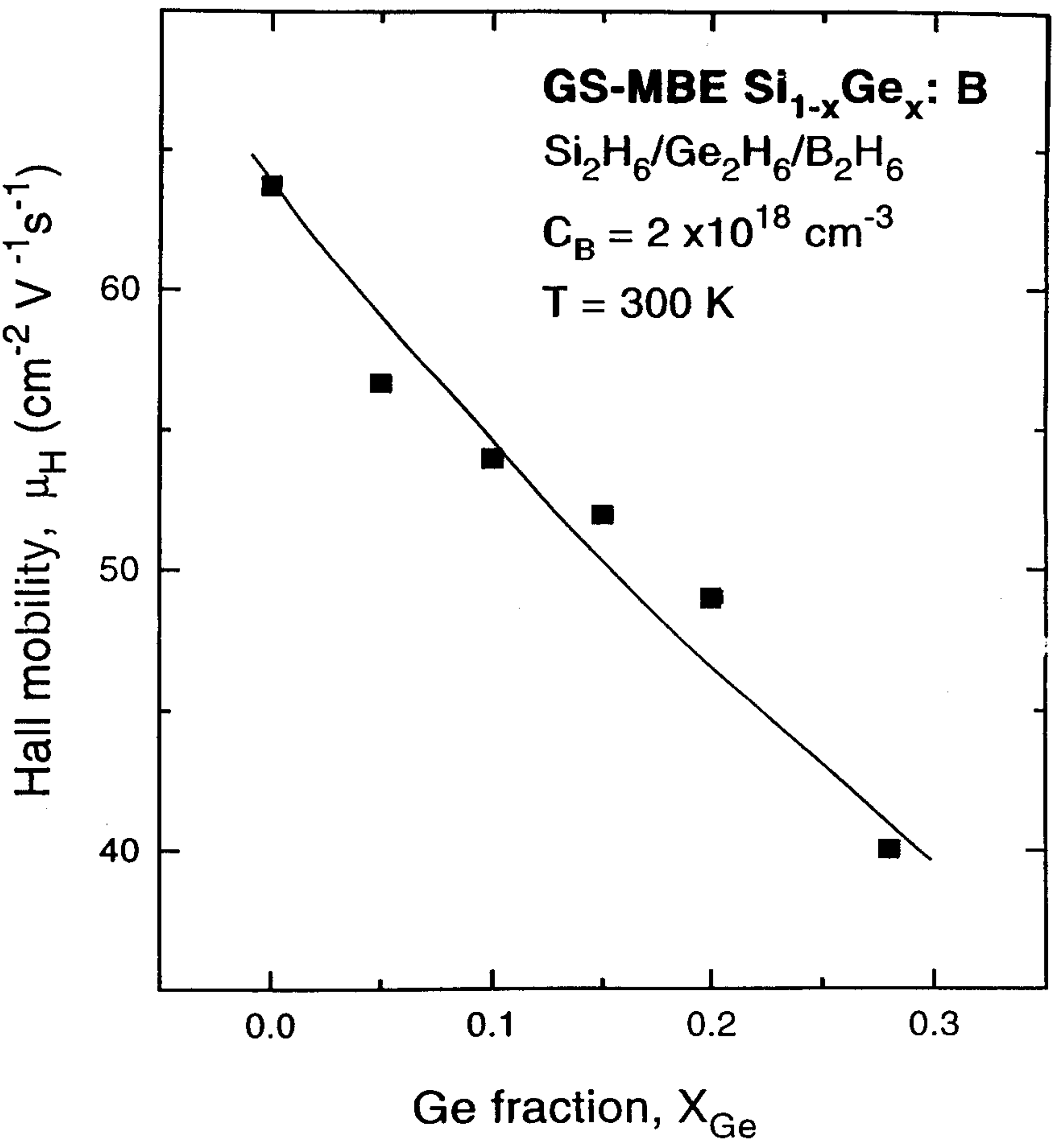
$a_{\parallel, SiGe} = 0.54312 \pm 0.00002$ nm

$\therefore \frac{\Delta a}{a_{Si}} \leq 4 \times 10^{-5}$!

$\Gamma_{\parallel} = 24.5$ arc-s, $\Gamma_{\omega} = 24.9$ arc-s, $\Gamma_{\omega-2\theta} = 24.7$ arc-s

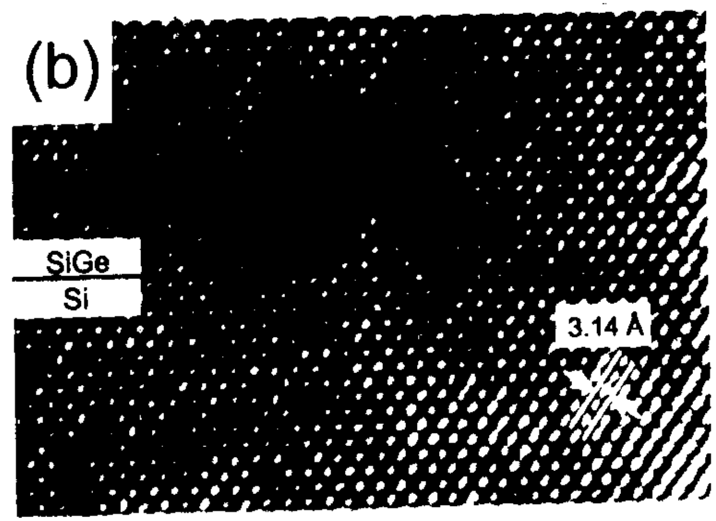


GS-MBE $Si_{1-x}Ge_x$: B
$Si_2H_6/Ge_2H_6/B_2H_6$
$C_B = 2 \times 10^{18}\ cm^{-3}$
T = 300 K
$\gamma = \mu_H / \mu_c = \langle \tau^2 \rangle / \langle \tau \rangle^2$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Hall scattering factor, γ
0.0
0.1
0.2
0.3
Ge fraction, X_{Ge}



GS-MBE $Si_{1-x}Ge_x$: B
$Si_2H_6/Ge_2H_6/B_2H_6$
$C_B = 2 \times 10^{18}$ cm^{-3}
T = 300 K
Hall mobility, μ_H (cm^{-2} $V^{-1}s^{-1}$)
60
50
40
0.0
0.1
0.2
0.3
Ge fraction, X_{Ge}

GS-MBE $Si_{1-x}Ge_x/Si(001)$



$X = 0.18$, $T_s = 500$ °C