

Effect of Sb on the Properties of GaInP Top Cells

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- Background
 - Efficiency of GaInP/GaAs tandem cells:
effect of top cell band gap
 - Why Sb?
- Result
 - Properties of Sb:GaInP
 - Sb:GaInP top cells
 - Sb:GaInP/GaAs tandem cells
- Summary

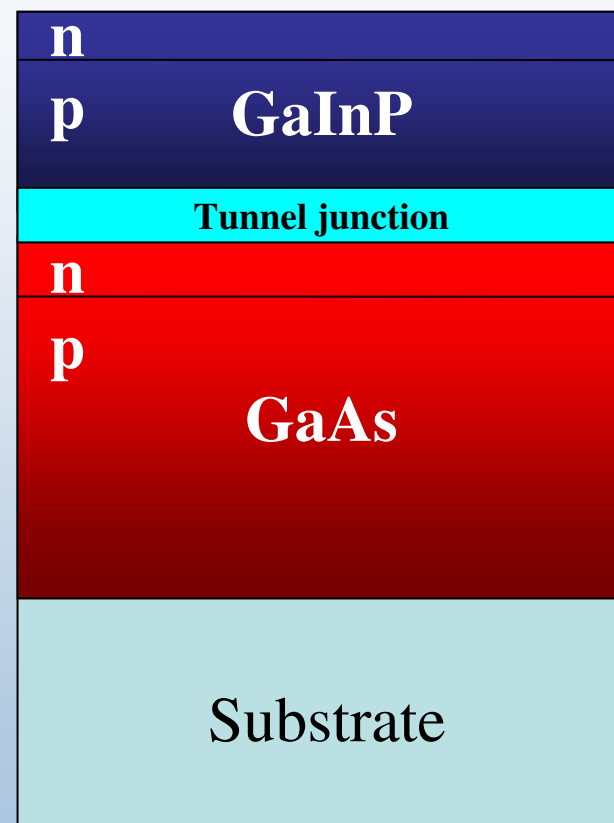
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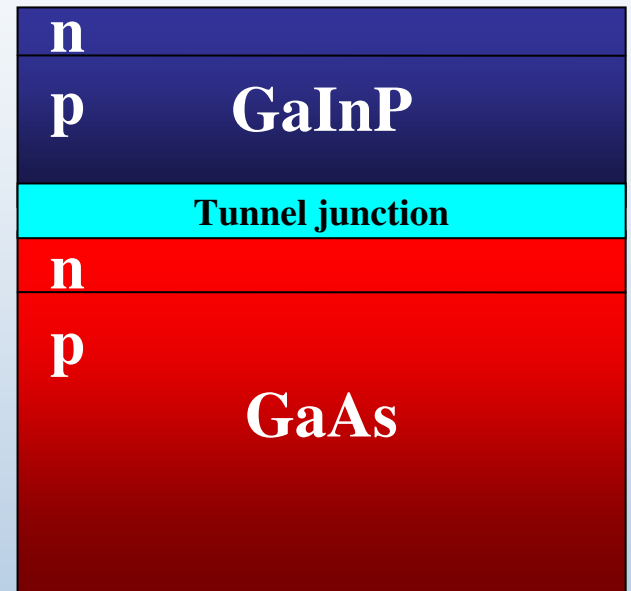
A Bit of History

- In 1984 - invention of GaInP/GaAs tandem cell. (Olson)
- In 1989 - 27.3% (Olson et al.)
- In 1993 - 29.5% (Bertness et al.)
- In 1996 - production of first commercial GaInP/GaAs cell (Spectrolab, et al.)
 - Space applications, Mars rovers
 - Terrestrial concentrator applications
- In 1997 - 30.3% AM1.5G (Takamoto et al.)



GaInP/GaAs tandem cell

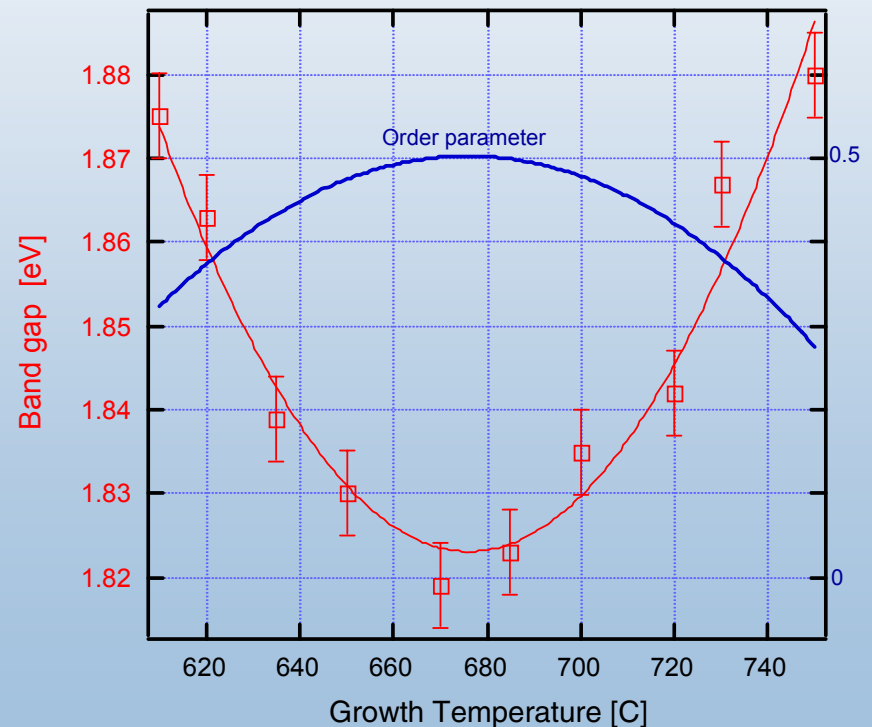
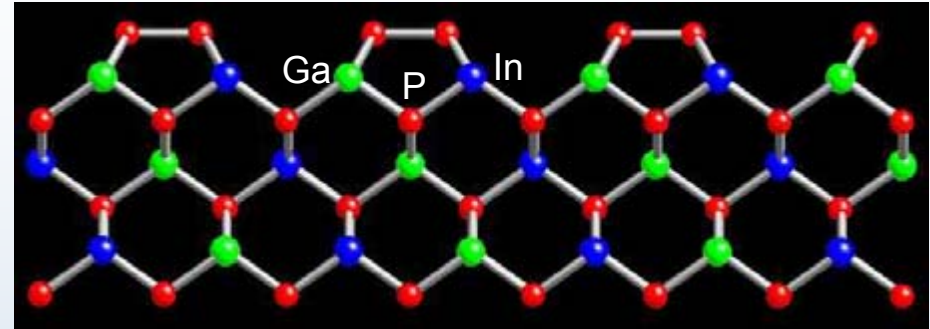
- Ideal top cell band gap for a GaAs bottom cell is $\sim 1.9\text{eV}$ ($\sim 2\text{eV}$ AM0).
- Typical band gap of GaInP is $\sim 1.8\text{eV}$ which reduces the ultimate efficiency by about 1 point.



Ordering in GaInP

- Band gap shift
 - caused by CuPt ordering of Ga and In on the Group III sublattice.
- Order parameter and band gap energy varies with
 - growth temperature
 - growth rate,
 - PH_3 partial pressure,
 - substrate orientation
 - **Type and concentration of shallow dopants.**

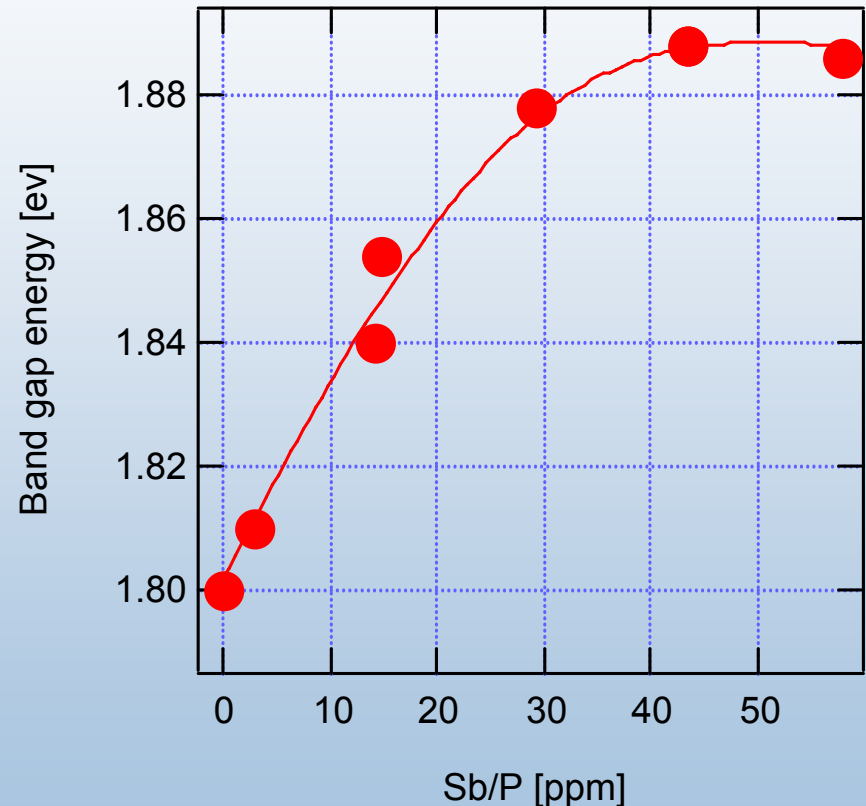
(Kurtz et al. JEM 1994)



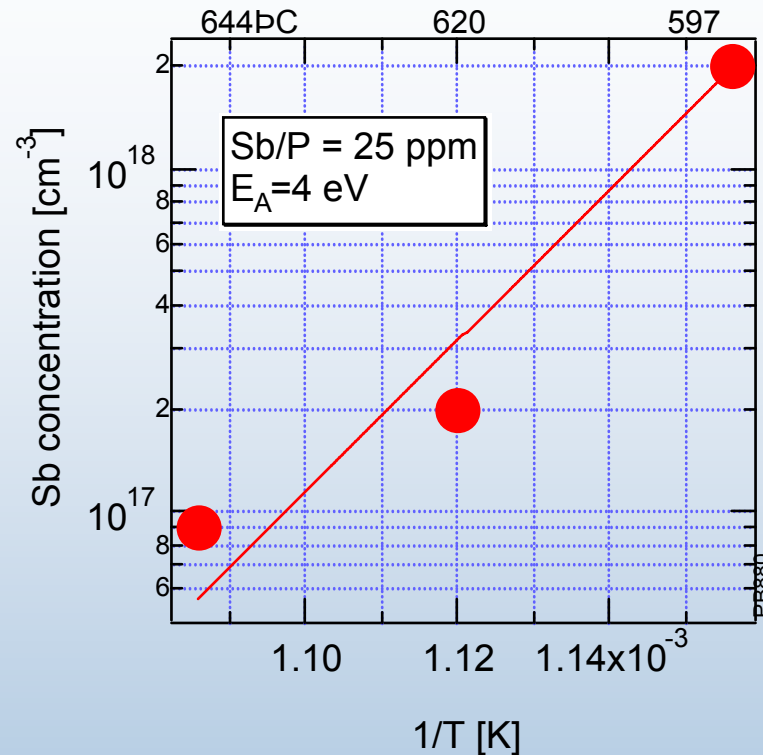
Effect of Sb on the Bandgap of GaInP

- Addition of Sb (TESb) during growth can hinder the ordering process and increase the band gap*
- Effect controlled by ratio of TESb to PH_3 (Sb/P)
- Effect is largest for
 - B-miscut substrates
 - $T_g \sim 625^\circ\text{C}$

*Shurtleff et al. APL (1999)

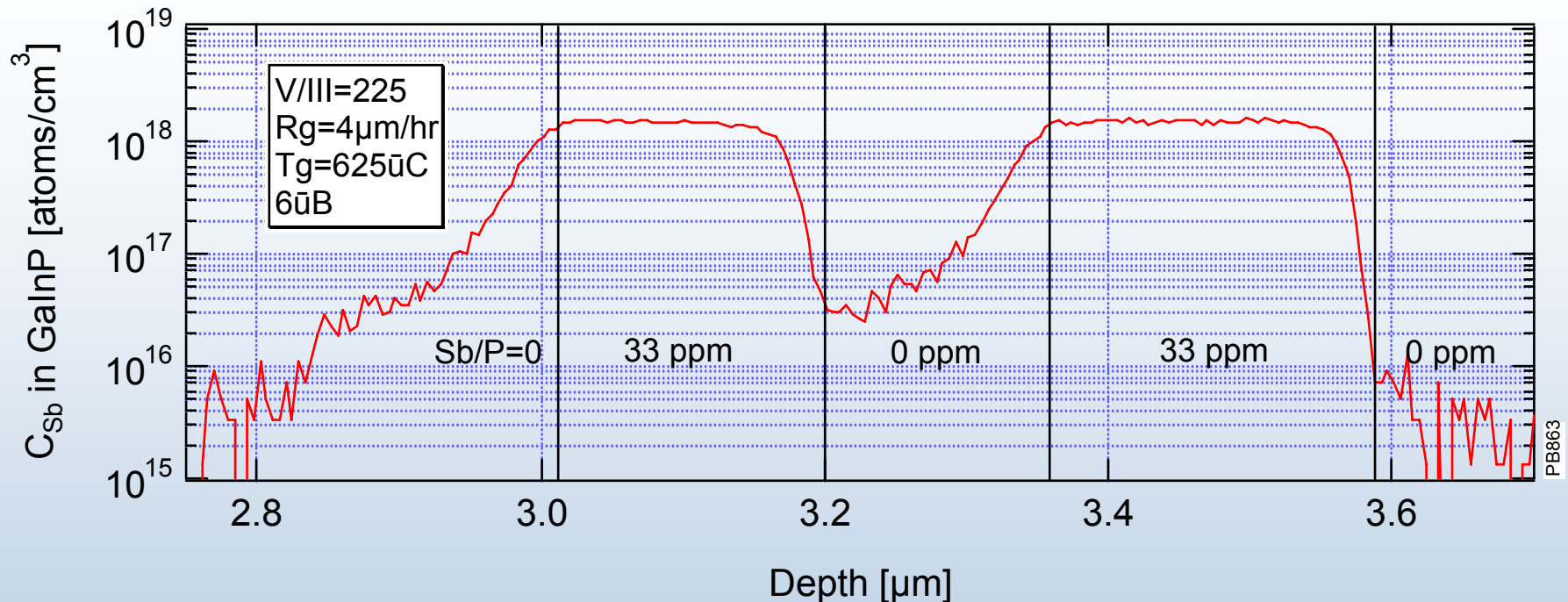


Sb incorporation vs Tg



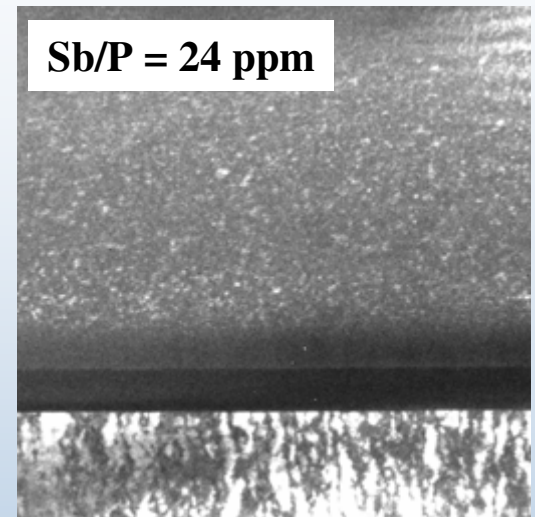
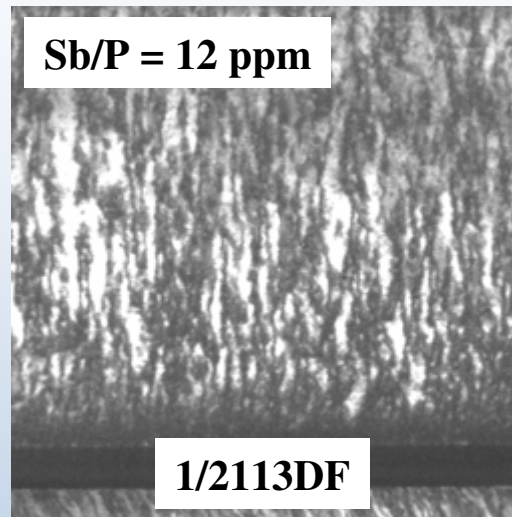
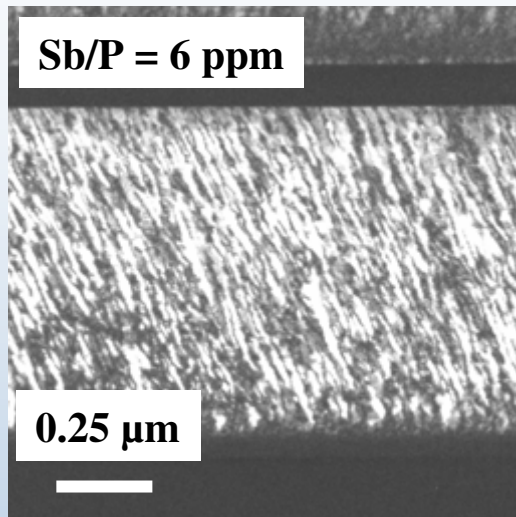
- Under conditions used for top cell, $C_{Sb} = \sim 2 \times 10^{17} \text{cm}^{-3}$
- Activation energy $\sim 4 \text{eV}$, comparable to that of the $1/P_{Sb}$.

Surface Concentration Θ_{Sb} on GaInP



- The $1/e$ decay length $L=23\text{nm}$
- Surface segregation coefficient $R = \exp(-a_0/L) = 0.988$
- Sb surface concentration $\theta_{\text{Sb}} \propto C_{\text{Sb}}/(1-R)$, $\theta_{\text{Sb}} = 0.006$
- Implies (001) terrace not occupied with Sb-Sb dimers
- Theoretical work - preferred Sb attachment at B-type steps, (Batyrev, PRL 2005)

Ordered domain structure

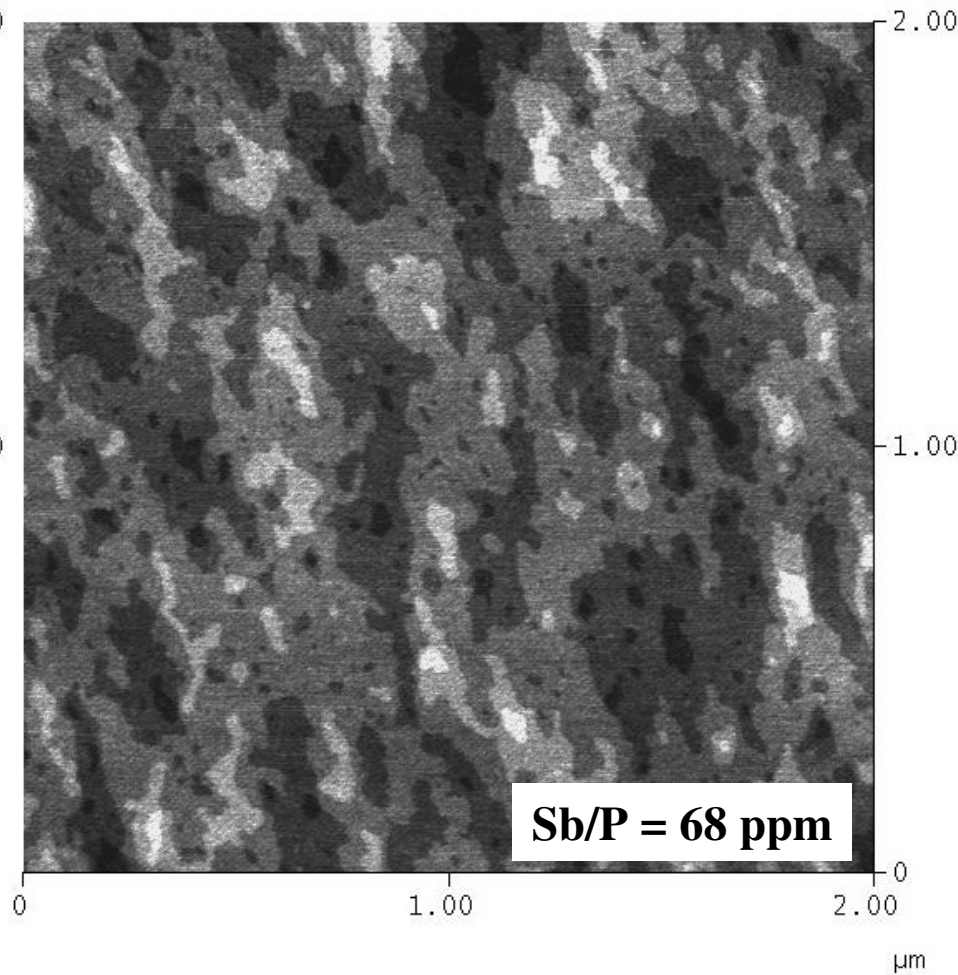
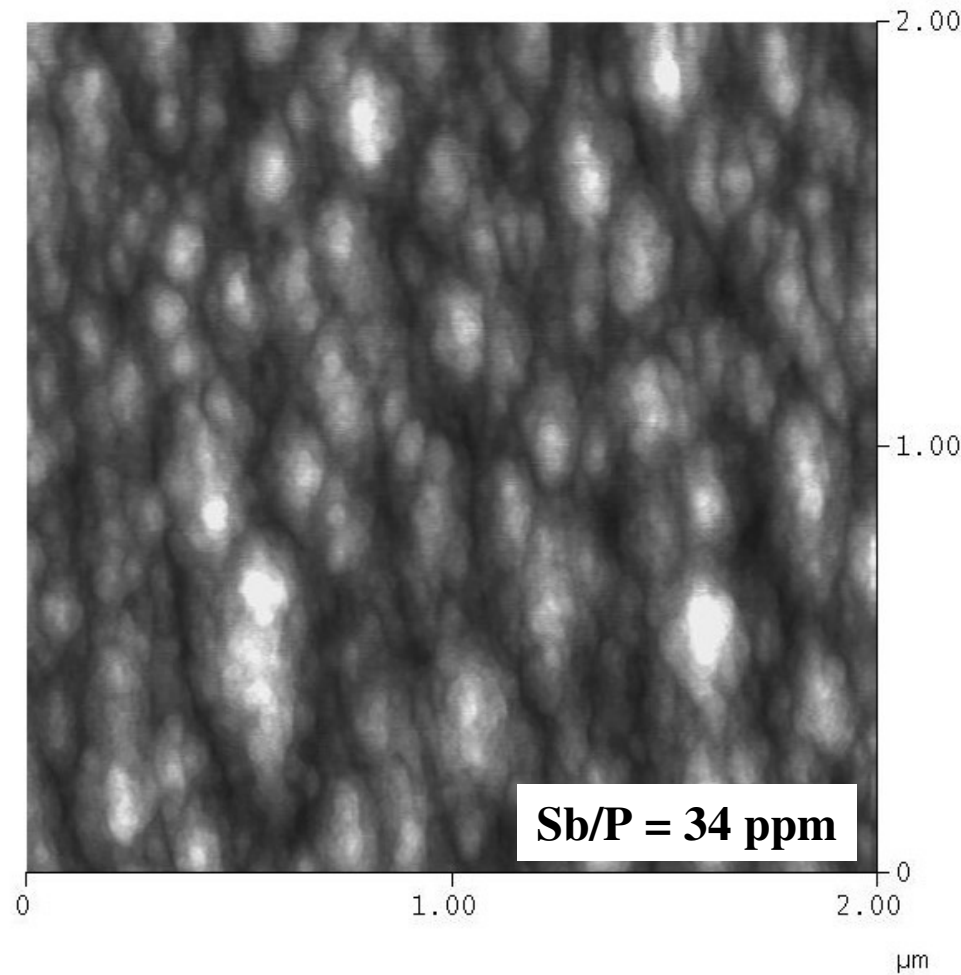


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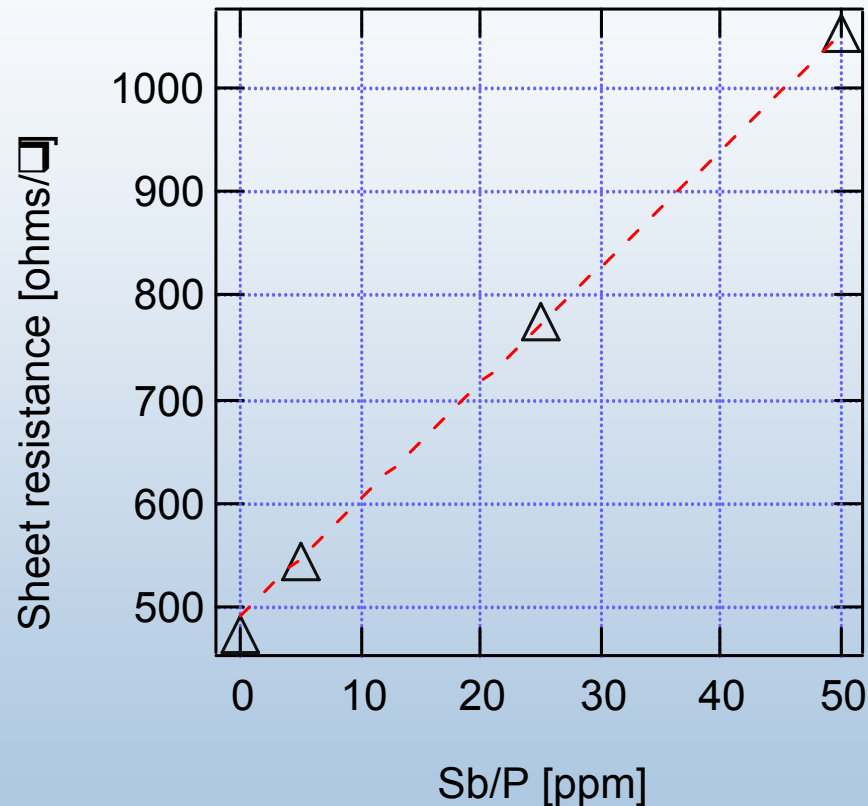
- Tilted domain boundaries result from step flow (Ishimura, et al PRB 51 p9707)

Surface morphologies of Sb:GaInP on singular GaAs(100)

- For intermediate Sb, surface composed of asymmetric **hillocks, 5 to 7nm high**, bounded by low angle B-type facets, Friedman et al APL (1993).
- For higher Sb, surface composed of large terraces separated by **ML steps (0.28nm)**.
- This implies that Sb raises the energy of B-type steps on GaInP(100).

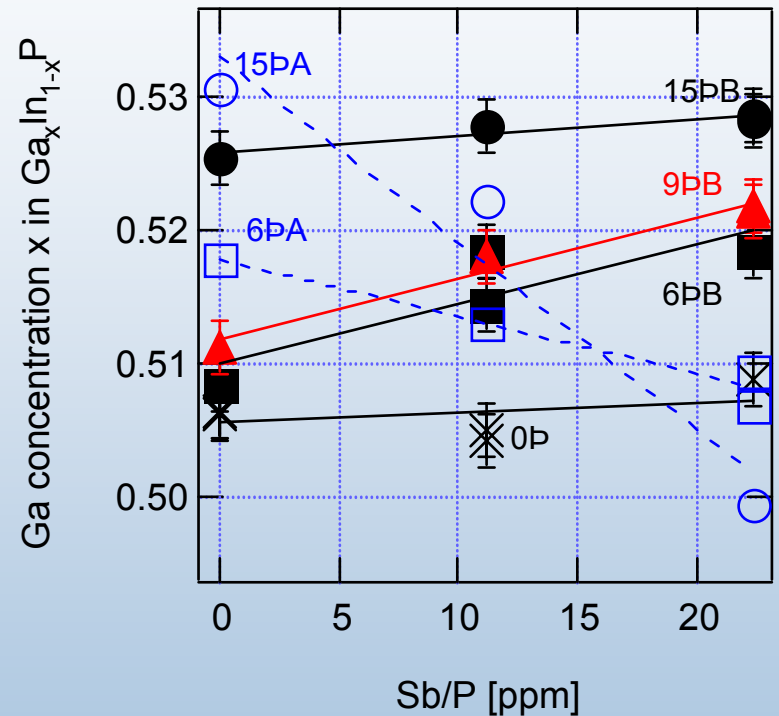
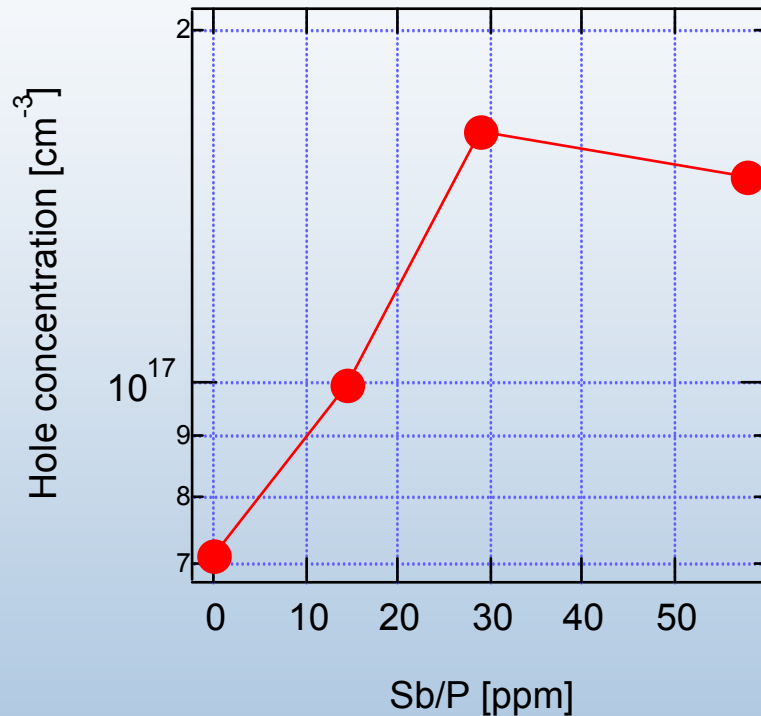


Effect of Sb on Se incorporation



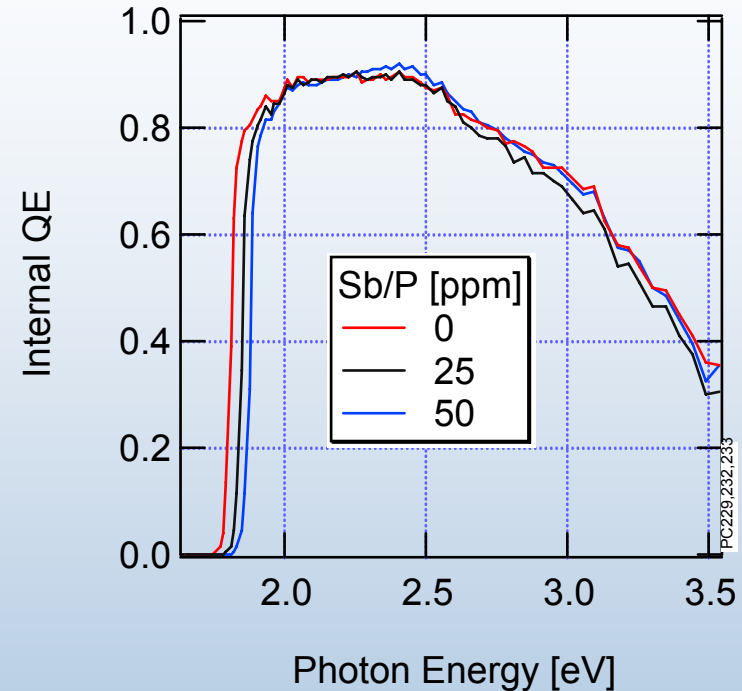
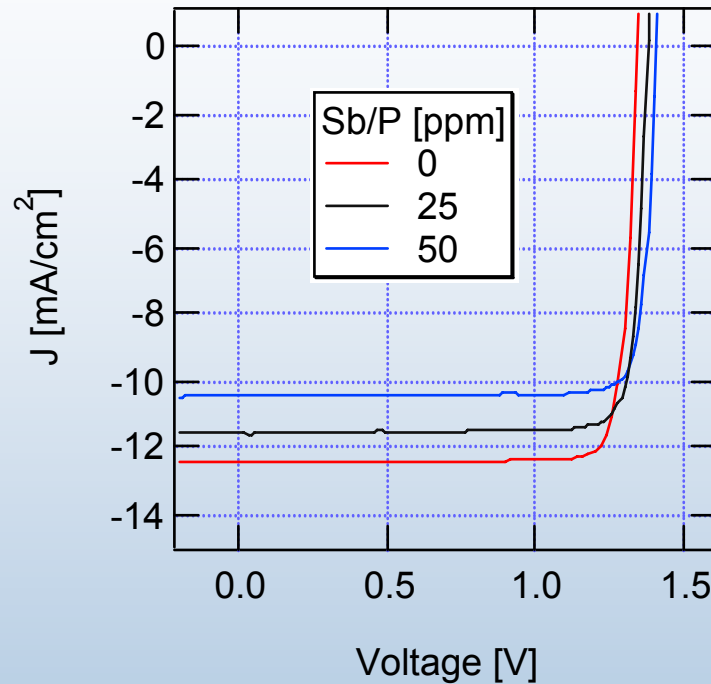
- Sb, P and Se compete for group V lattice sites
- $C_{Se} \propto \alpha F_{Se} / (1 + \alpha F_{Se} + \beta F_{Sb} + \gamma F_P)$

Effect of Sb on Group III Site Occupations



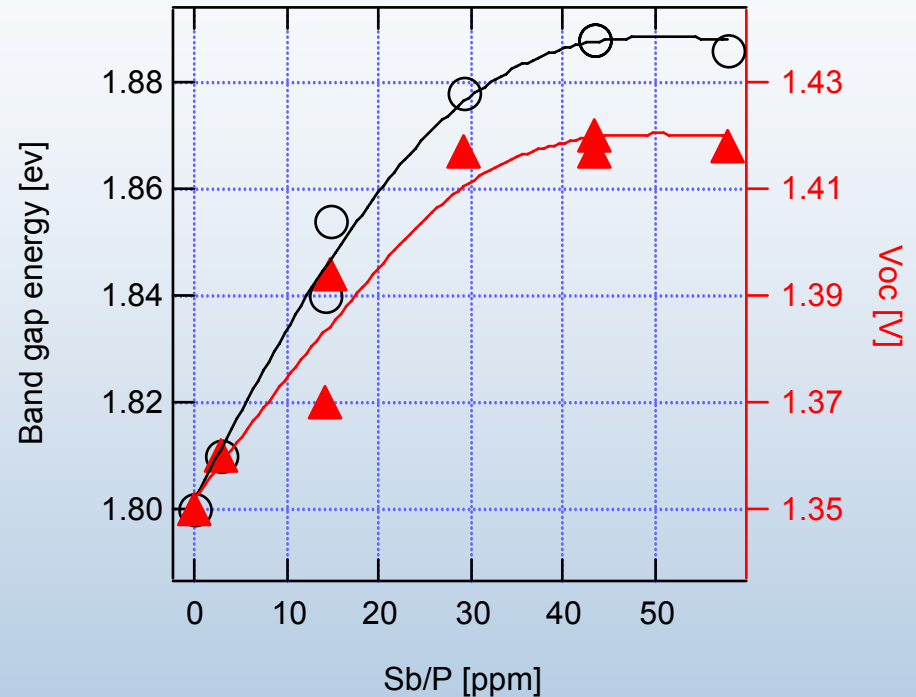
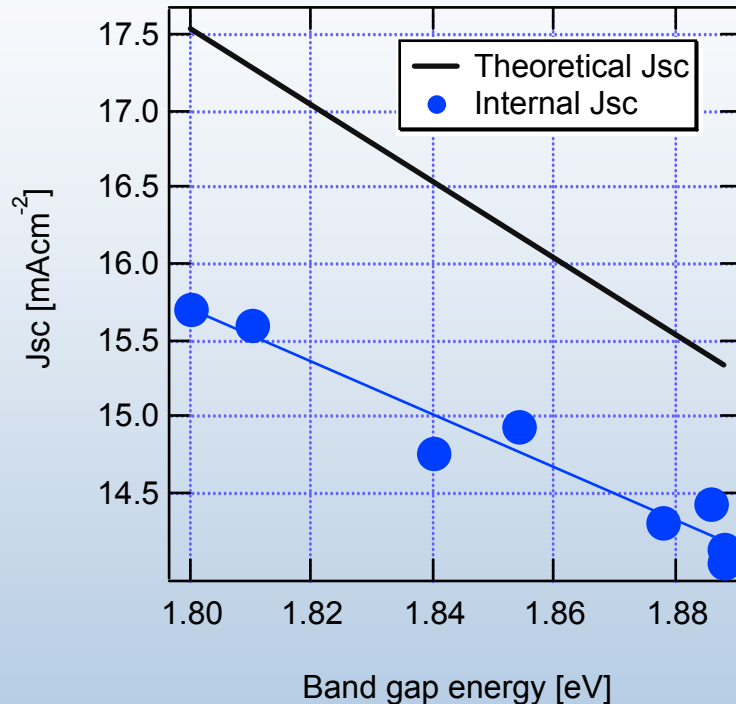
Mechanism?

Sb-doped GaInP top cells



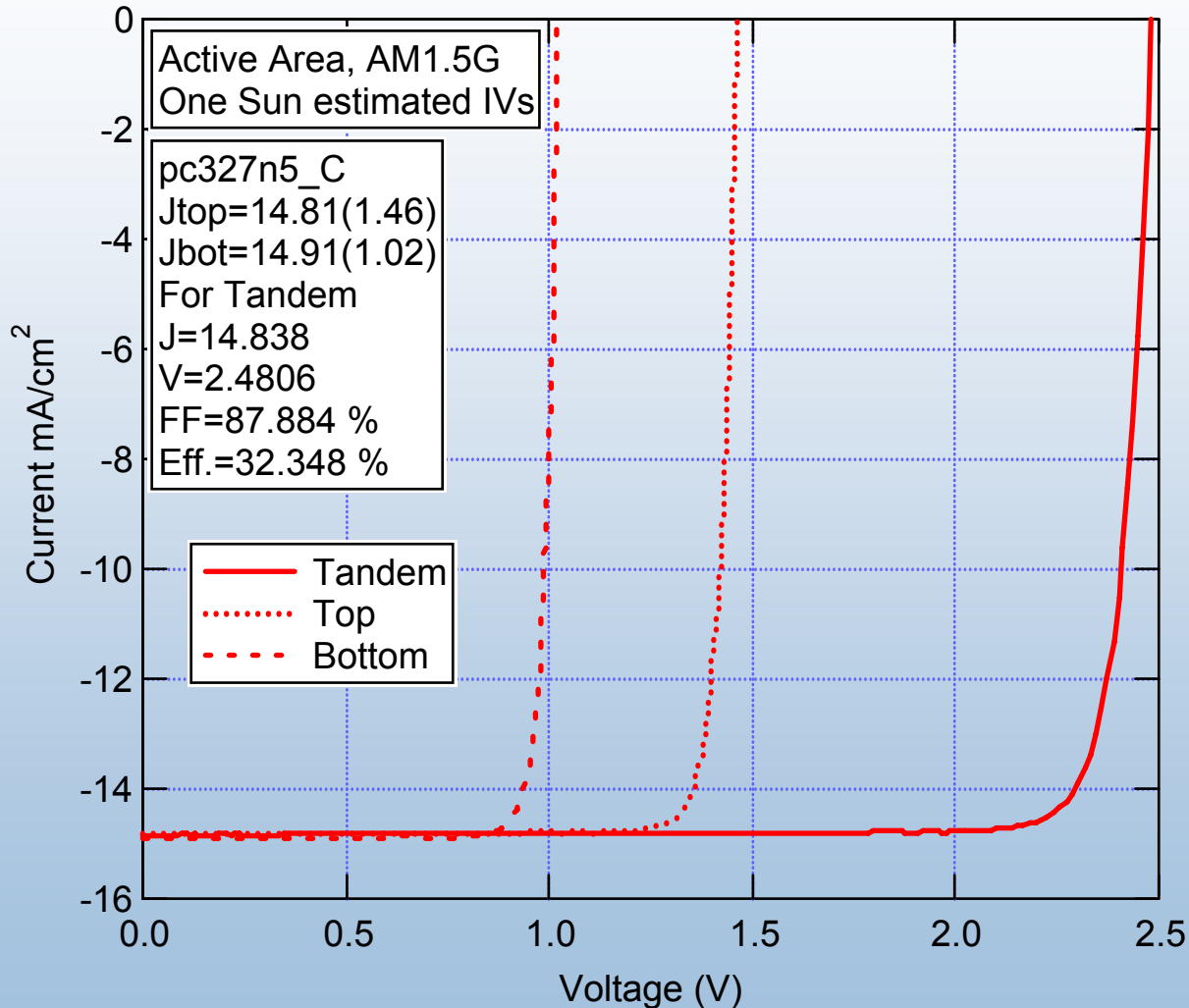
- The base/emitter/window thicknesses are $2\mu\text{m}$, $0.1\mu\text{m}$ and $0.025\mu\text{m}$, respectively
- The base p varies from $7e16$ to $\sim 2e17 \text{ cm}^{-3}$
- The emitter sheet resistance varies from 500 to $1000 \Omega/\square$.

Top cell device parameters vs Sb



- Internal J_{sc} decreases with E_g slower than expected.
- V_{oc} increases more slowly than E_g .

Sb-doped GaInP/GaAs tandem cells



Total Area 15% metal

$$J_{sc} = 12.388 \text{ mAcm}^{-2}$$

$$V_{oc} = 2.476 \text{ V}$$

$$Ff = 86.95\%$$

$$Eff = 26.67\%$$

- Top cell base
 - Thickness = 2μm
 - $E_g = 1.89 \text{ eV}$,

Summary

- Sb can be used to increase V_{oc} of a GaInP top cell.
- The photovoltaic quality of GaInP is relatively unaffected by the presence of Sb.
- Sb-doped GaInP/GaAs tandem cells show promise for achieving efficiencies over 32%.

Acknowledgements

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