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Accelerating the next technology revolution.

Anti-Phase-Boundary Defects in GaAs-on-Si Films: 1. characterization by SHG 2. suppression by ART

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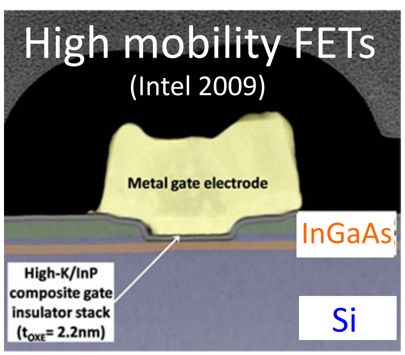
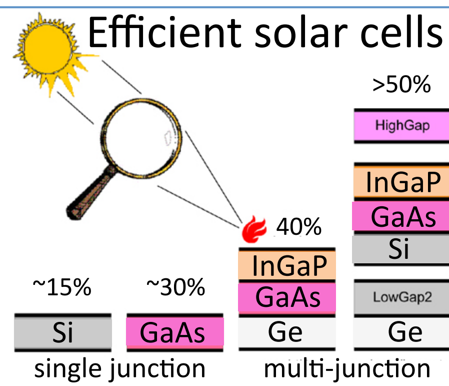
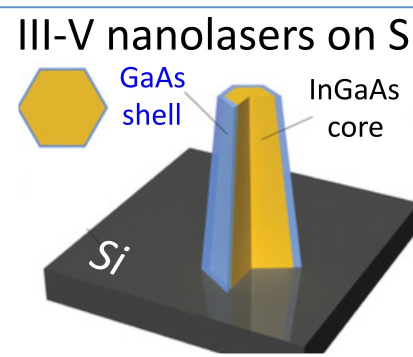
[2]*GlobalFoundries, Inc.*

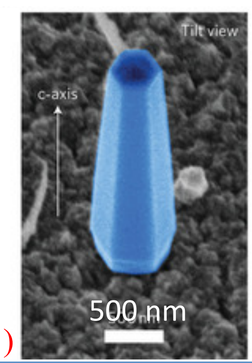
[3]*Sematech and Intel Corp.*

The microelectronics industry is trying to marry III-V and Column IV semiconductors via hetero-epitaxy to combine the favorable properties of each







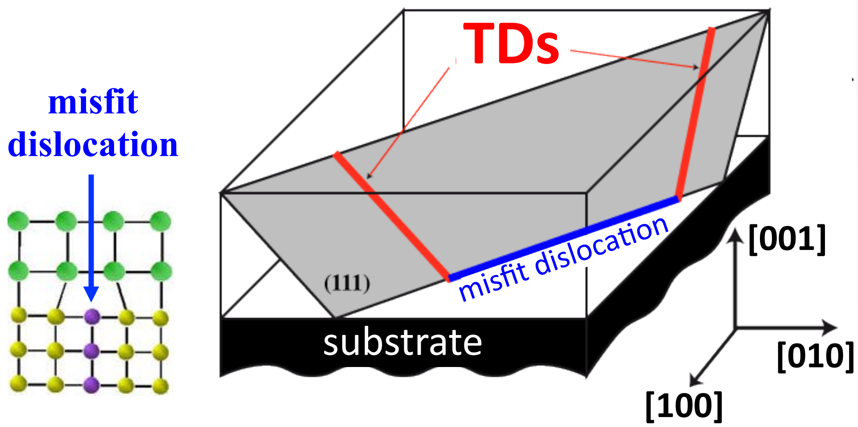


Chen, *Nat. Phot.* **5**, 170 (2011)

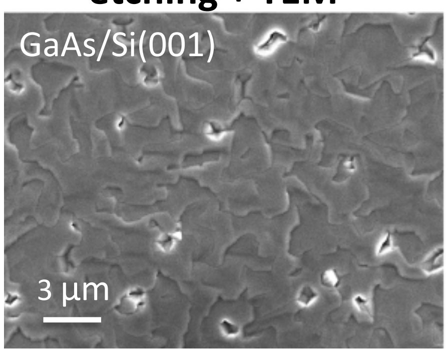
GaAs/Si interfaces are susceptible to formation of defects

Threading Dislocations (TDs)

Where: any hetero-interface
Cause: lattice mismatch



Characterization: selective etching + TEM



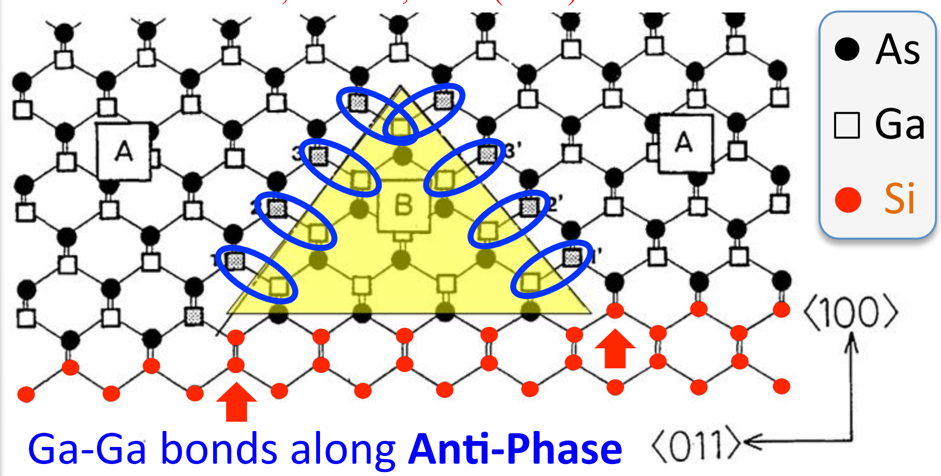
Hsu, *Nanotech.* 23, 495306 (2012)

sub-strate	lattice mismatch w. GaAs	typical TDD [cm^{-2}]
Si (001)	4%	$>10^9$
Ge (001)	<1%	$<10^8$

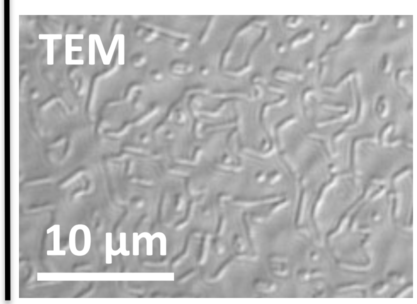
Anti-Phase Domains (APDs)

Where: polar-on-nonpolar hetero-interfaces
Cause: single-atom steps, nonpolar substrate (⬆)

Kawabe, JJAP **26**, L944 (1987)



Ga-Ga bonds along **Anti-Phase Boundaries** (**APB**s) degrade carrier mobility

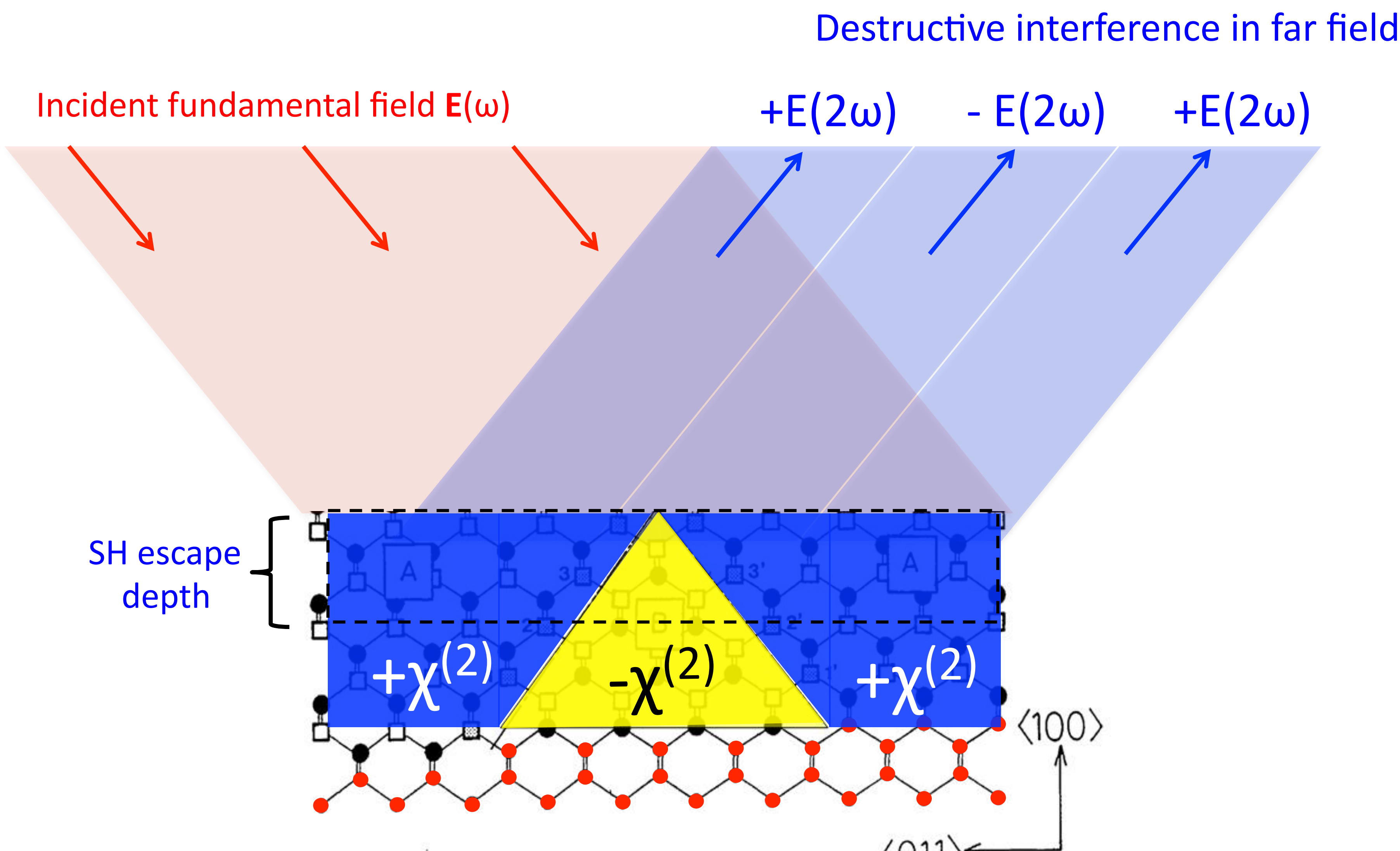


Brammertz, *TSF* **517**, 148 (2008)

TDs and APBs are challenging to distinguish in TEM micrographs

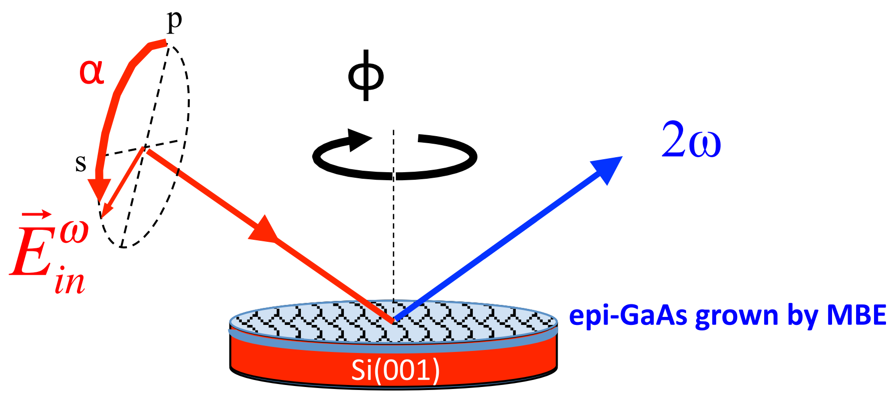
To evaluate strategies for suppressing these defects, a fast, noninvasive diagnostic that clearly distinguishes APBs from TDs is needed

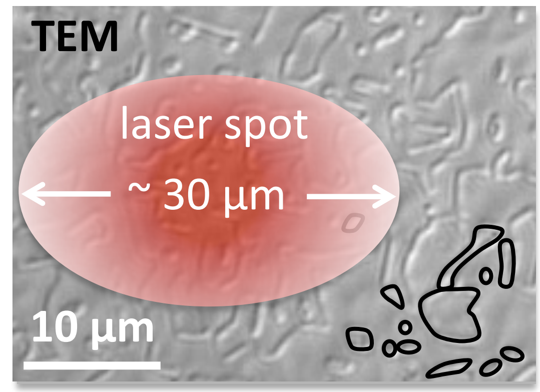
Neighboring APDs generate SH fields of opposite sign



Previous related work: Amzallag, *APL* **66**, 982 (1995)

SHG characterizes APBs sensitively and non-invasively

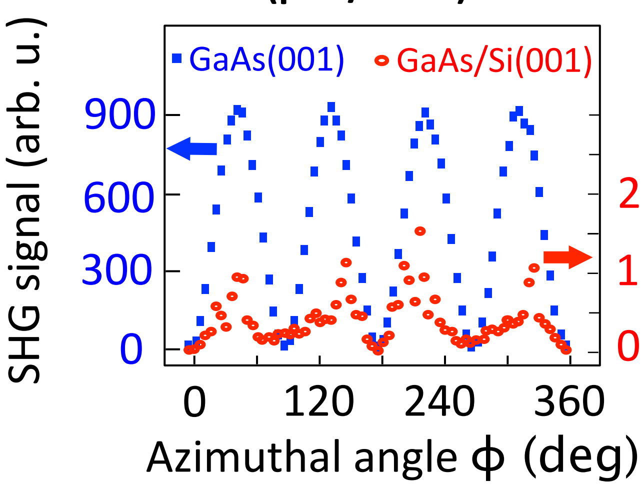




APDs: 0.1 – 2 µm

sample azimuthal rotation

(p-in/s-out)

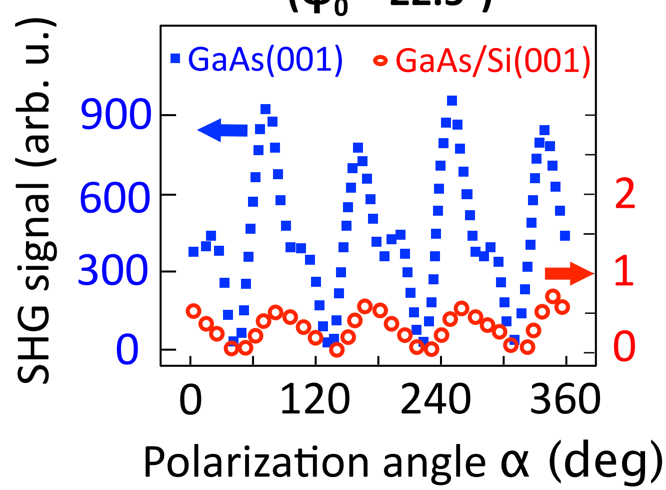


$I_s(2\omega)\ \alpha\ |\sin 2\phi|^2$

[Yamada. *Phys. Rev. B* **49**, 14372 (1994)]

incident polarization rotation

(ϕ_0 = 22.5°)



$I_s(2\omega)\ \alpha\ |\cos\alpha(f_c t_p \cos 2\phi_0 \cos\alpha + t_s \sin 2\phi_0 \sin\alpha)|^2$

To test SHG sensitivity to TD Density (TDD), we prepared $In_xGa_{1-x}As/GaAs$ samples

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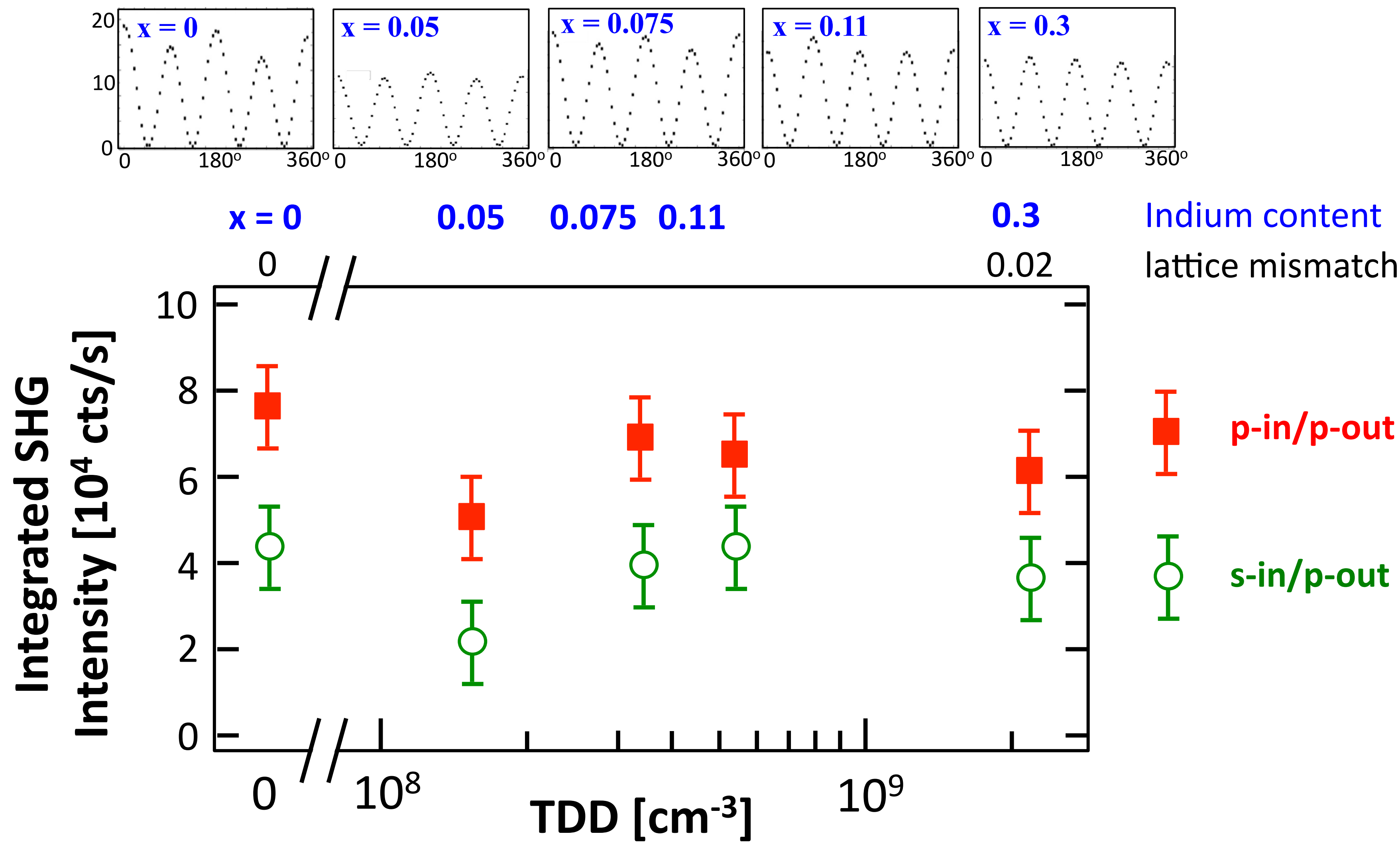
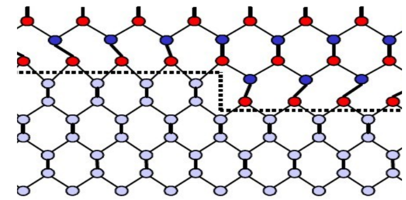
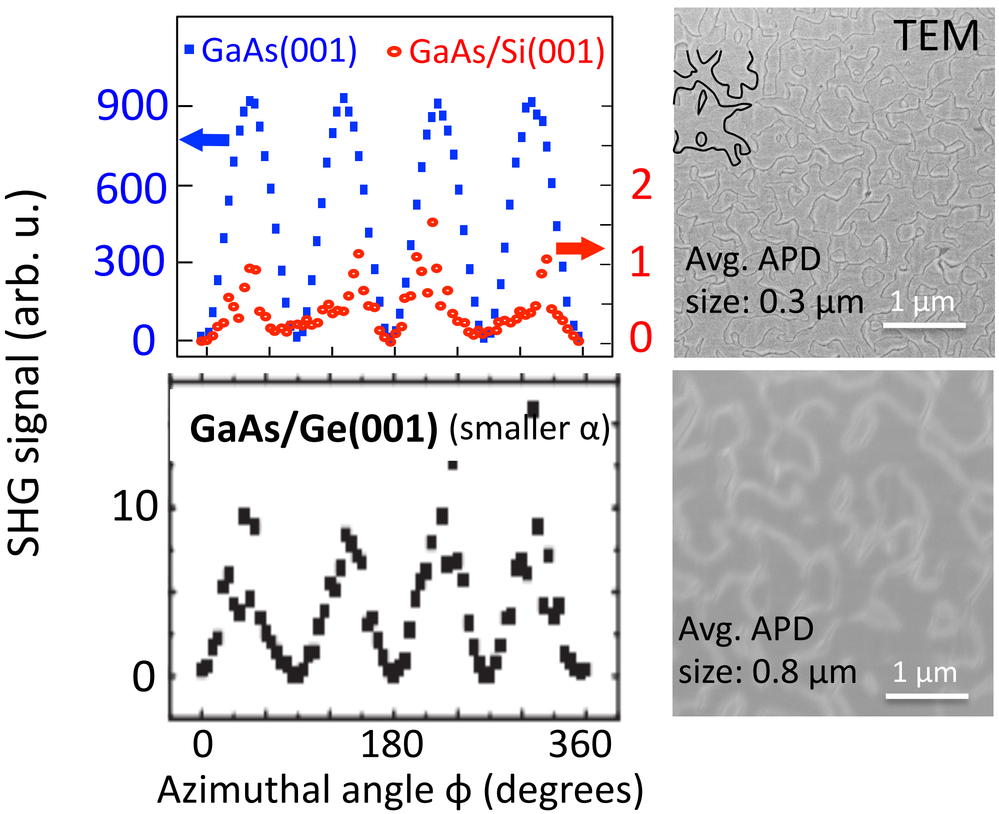


Conclusion: SHG is uncorrelated with TDD

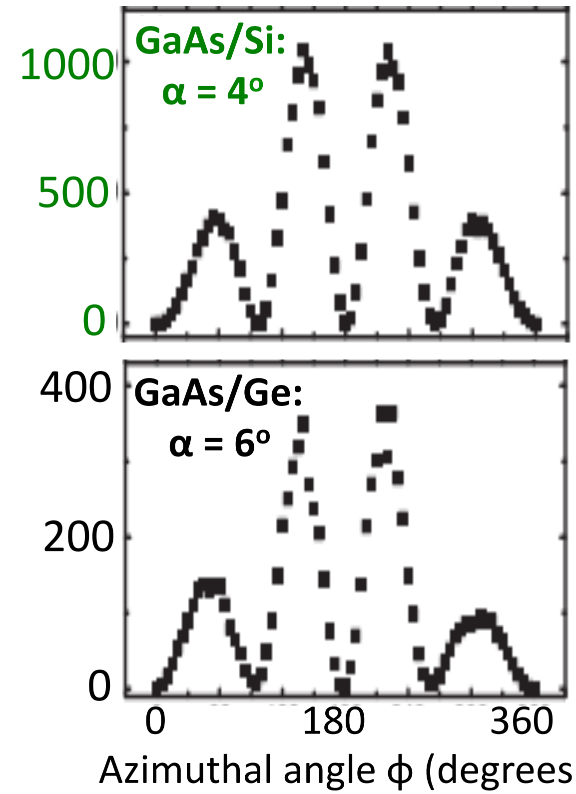
Substrate off-cut angle α strongly affects APD density & SHG suppression



α < 1°: single-atom steps dominate;
SHG suppression correlates with APD density



α ≥ 4°: double-atom steps dominate;
APDs suppressed, SHG recovers

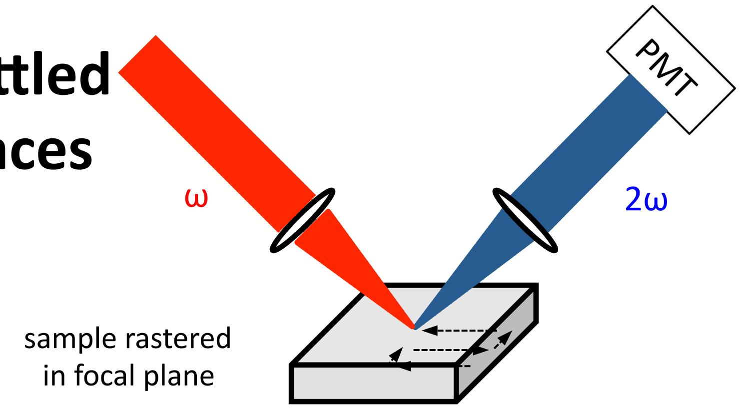


No APBs evident by TEM

	GaAs	GaAs/Si(001)	GaAs/Ge(001)	GaAs/Si: 4°	GaAs/Ge: 6°
<SHG intensity>	1	2.4×10^{-3}	7.7×10^{-3}	0.74	0.24
Roughness nm	0.9	1.0	5.8	1.8	16
TDD /cm^{-2}	N/A	8×10^{9}	2.5×10^{8}	5.5×10^{8}	2.4×10^{7}

Scanning SHG microscope yields mottled SHG response from APD-laden surfaces

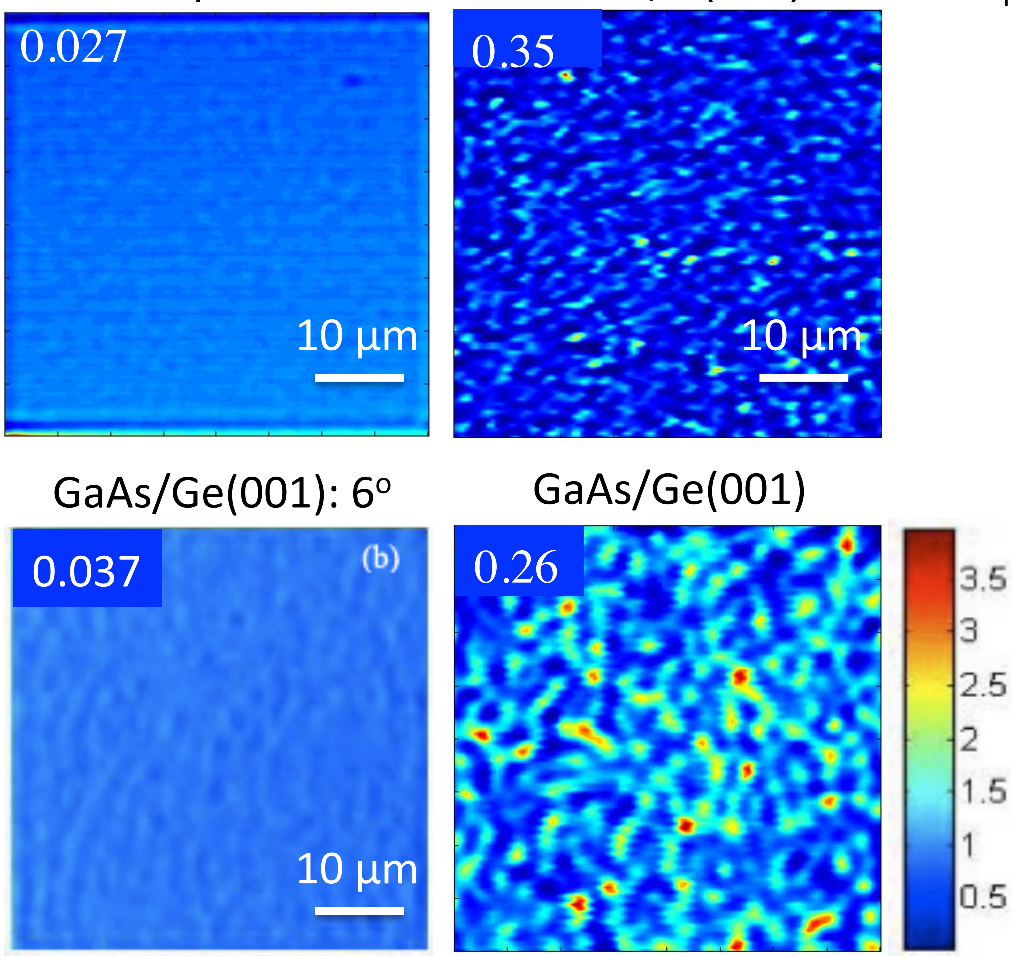
Lei *et al.*, APL **102**, 152103 (2013)



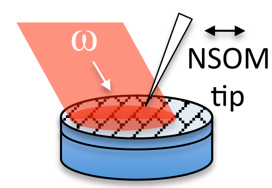
St. Dev. → of SHG intensity

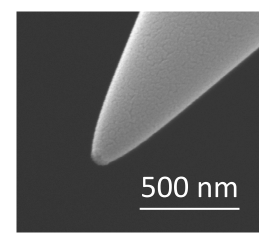
GaAs/GaAs | GaAs/Si(001)

GaAs/Ge(001): 6° | GaAs/Ge(001)



- The SHG images are NOT direct maps, but rather higher-order moments, of the APD distribution.
- **Bright areas** indicate dominance of one type of domain within the laser spot.
- **Dark areas** indicate equal areas of $+\chi^{(2)}$ and $-\chi^{(2)}$ domains within the laser spot.
- **SHG NSOM*** may be able to image individual APDs directly.





*Smolyaninov, *Phys. Rev. B* **56**, 9290 (1997)
Bozhevolnyi, *Opt. Commun.* **150**, 49 (1998)

Growth of GaAs on exactly oriented Si(001) is preferred for high-volume manufacturing

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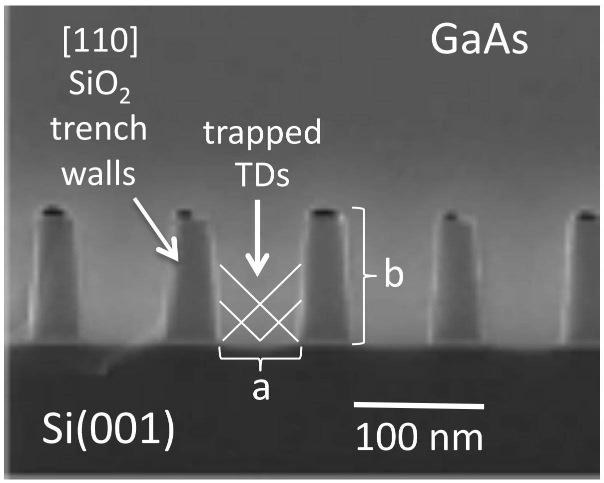
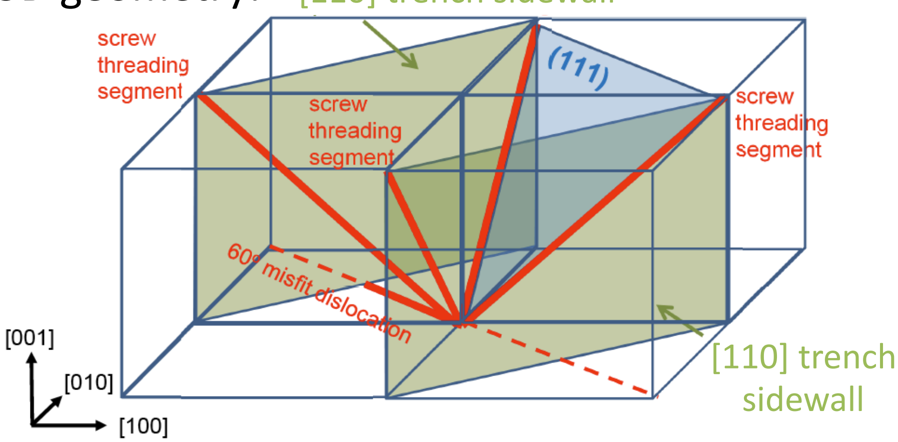
Aspect-Ratio Trapping (ART) is an established technique for suppressing TDs on Si(001)

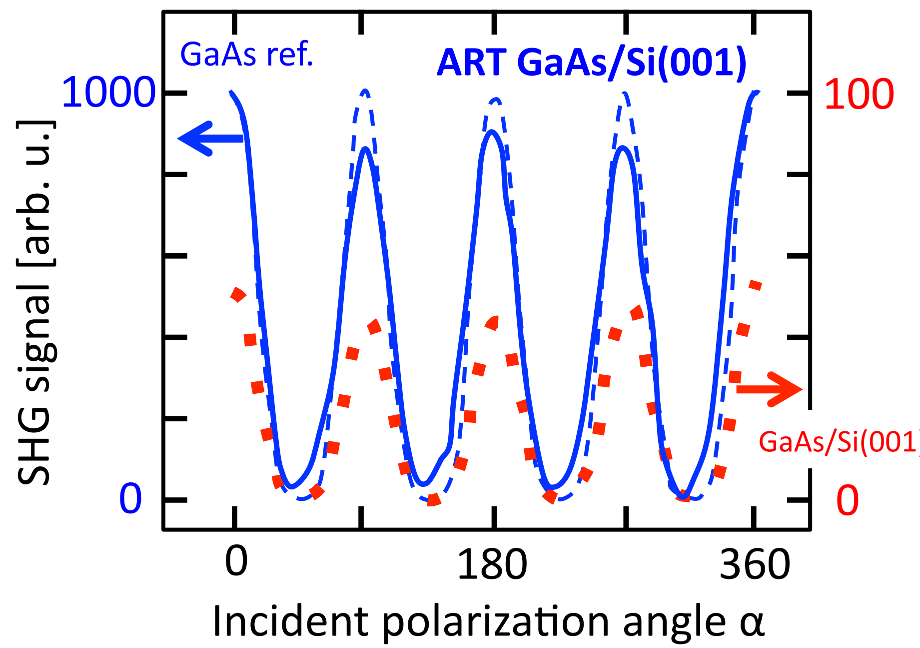
Fitzgerald, *J. Electron. Mater.* **20**, 839 (1991)



3D geometry:

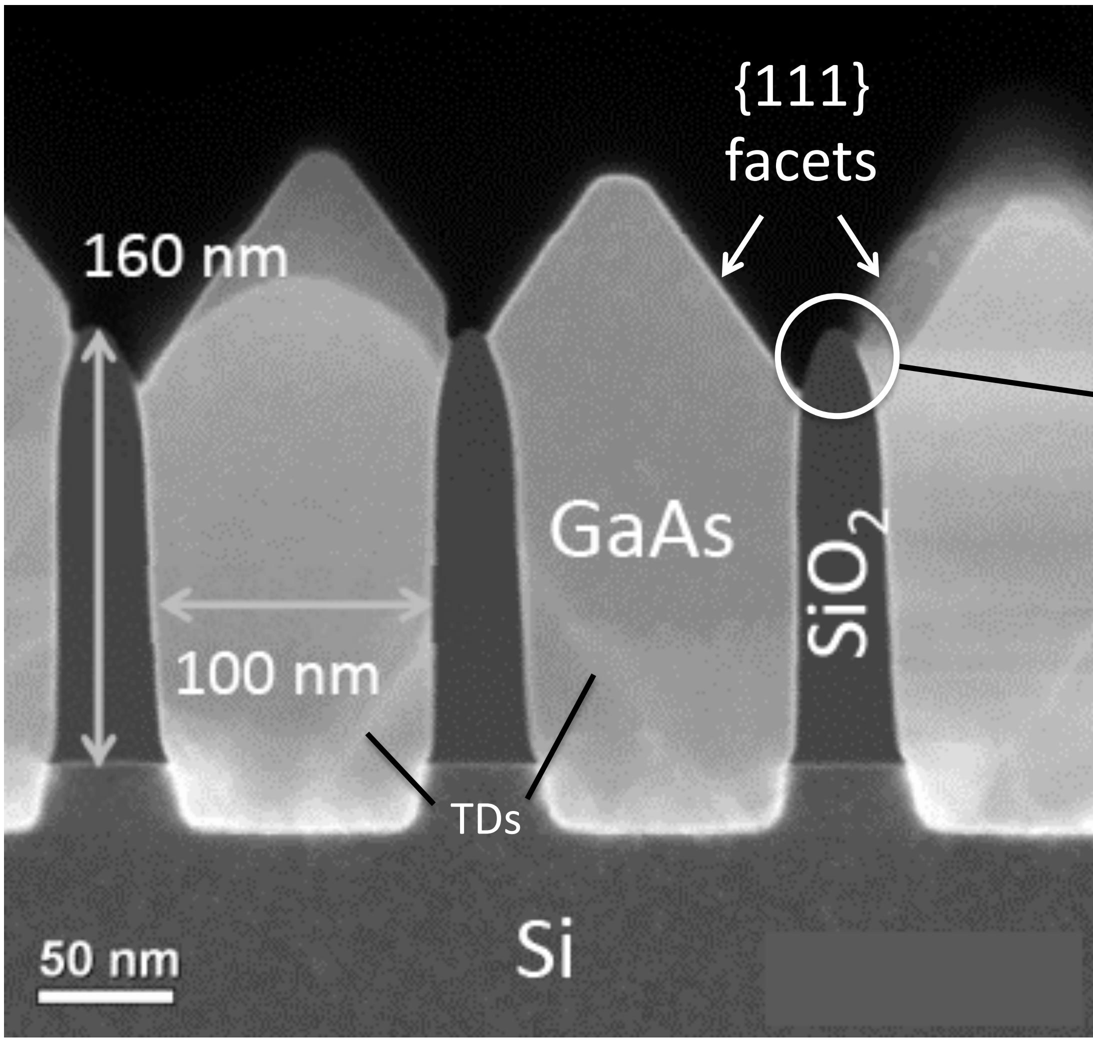


We found (serendipitously) that ART patterning of oriented Si(001) substrates also **dramatically suppresses APDs in GaAs epi-films**



Nearly complete recovery of GaAs reference SHG signal!

GaAs pillars evidently coalesce commen-surately into a single domain epi-layer



tapered sidewall with pliable Si-O bonds may encourage Ga-As bond formation when pillars merge

ART appears to solve 2 problems simultaneously!

SUMMARY

- SHG characterizes APDs in polar-on-nonpolar semiconductor epi-films sensitively, quickly, non-invasively and selectively.
- Scanning SHG microscopy indirectly probes APD size distribution; SHG-NSOM promises direct APD imaging.
- SHG APD probe helps develop methods to suppress APDs:
  e.g. 1. vicinal substrates; 2. ART
- Compared to RAS, SHG is equally useful as an *ex-situ* & *in-situ* APB probe, requires only a single-λ source for any material system, and enables microscopic (possibly single APD) imaging.

Lei *et al*., *Appl. Phys. Lett*. **102**, 152103 (2013)

Patent Pending

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