Heteroepitaxy of Orientation-patterned GaP on GaAs Templates for Frequency Conversion Applications

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GaP boasts excellent nonlinear properties making it suitable for terahertz (THz) and mid-IR generation by frequency down-conversion using quasi-phase-matching (QPM) schemes [1]. By growing OP-GaP on OP-GaAs templates by direct heteroepitaxy, the beneficial material properties of GaP can be combined with the high-quality substrates and mature processing techniques afforded by GaAs [2].

In this work, heteroepitaxy of OP-GaP on OP-GaAs templates prepared by a wafer bonding technique was performed using our low-pressure hydride vapor phase epitaxy (LPHVPE) reactor at 20 mbar and 710 °C. The effect on the growth by precursor gas flows was investigated to achieve good domain fidelity as well as high growth rate and crystalline quality. It was found that threading dislocations (TDs) caused by the 3.6% lattice mismatch between GaP and GaAs deteriorate the domain fidelity by enhancing the lateral growth rate of the $(00\bar{1})$ domains. Increasing the GaCl flow reduced the TD density and resulted in OP-GaP with good domain fidelity and a high growth rate of 57 µm/h (Fig. 1a). The crystalline quality of the OP-GaP growths were characterized by high resolution x-ray diffraction (HRXRD) reciprocal space mapping (RSM), in which the different domains can be resolved. A high crystalline quality of each domain is revealed by the low full width at half maximum (FWHM) value along the omega-direction in the RSM (Fig. 1b). THz transmission spectroscopy (TDS) was performed on a planar GaP reference sample grown on semi-insulating (SI) GaAs. The transmitted spectrum from the GaP layer was used to extract the conductivity in the THz range (0.2-0.9 THz). The conductivity was fitted to the Drude model (Fig. 1c) yielding a DC conductivity of 0.16 S/cm and a characteristic scattering time of 305 fs.

To summarize, OP-GaP was grown heteroepitaxially on wafer-bonded OP-GaAs template substrates by LPHVPE. High GaCl flows were used to achieve a high growth rate of 57 µm/h as well as vertical domain boundaries by suppressing the formation of threading dislocations. A high crystalline quality was revealed by HRXRD RSM, and results from TDS on GaP grown on SI-GaAs were presented. The results presented here indicate that direct heteroepitaxy of OP-GaP on OP-GaAs templates are a promising approach for QPM-enabled THz and mid-IR frequency generation.

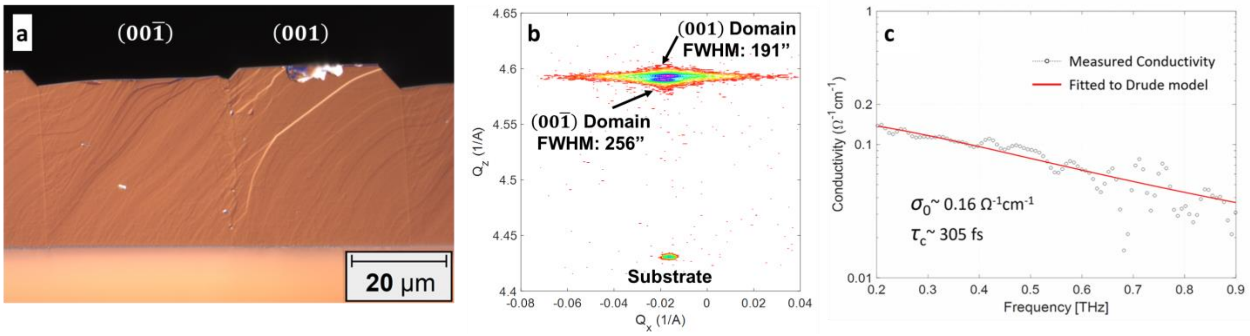

Fig. 1: (a) Microscopy image of OP-GaP on OP-GaAs template cross section grown with PH_3 = 50 sccm, and GaCl = 25 sccm. (b) HRXRD RSM of the OP-GaP growth on OP-GaAs template. (c) THz conductivity extracted from the THz transmission spectroscopy measurements and fitted to the Drude model.

References:

[1] P. G. Schunemann, K. T. Zawilski, L. A. Pomeranz, D. J. Creeden, P. A. Budni, *J. Opt. Soc. Am. B* **2016**, *33*, D36

[2] V. L. Tassev, S. R. Vangala, Crystals 2019, 9, 39

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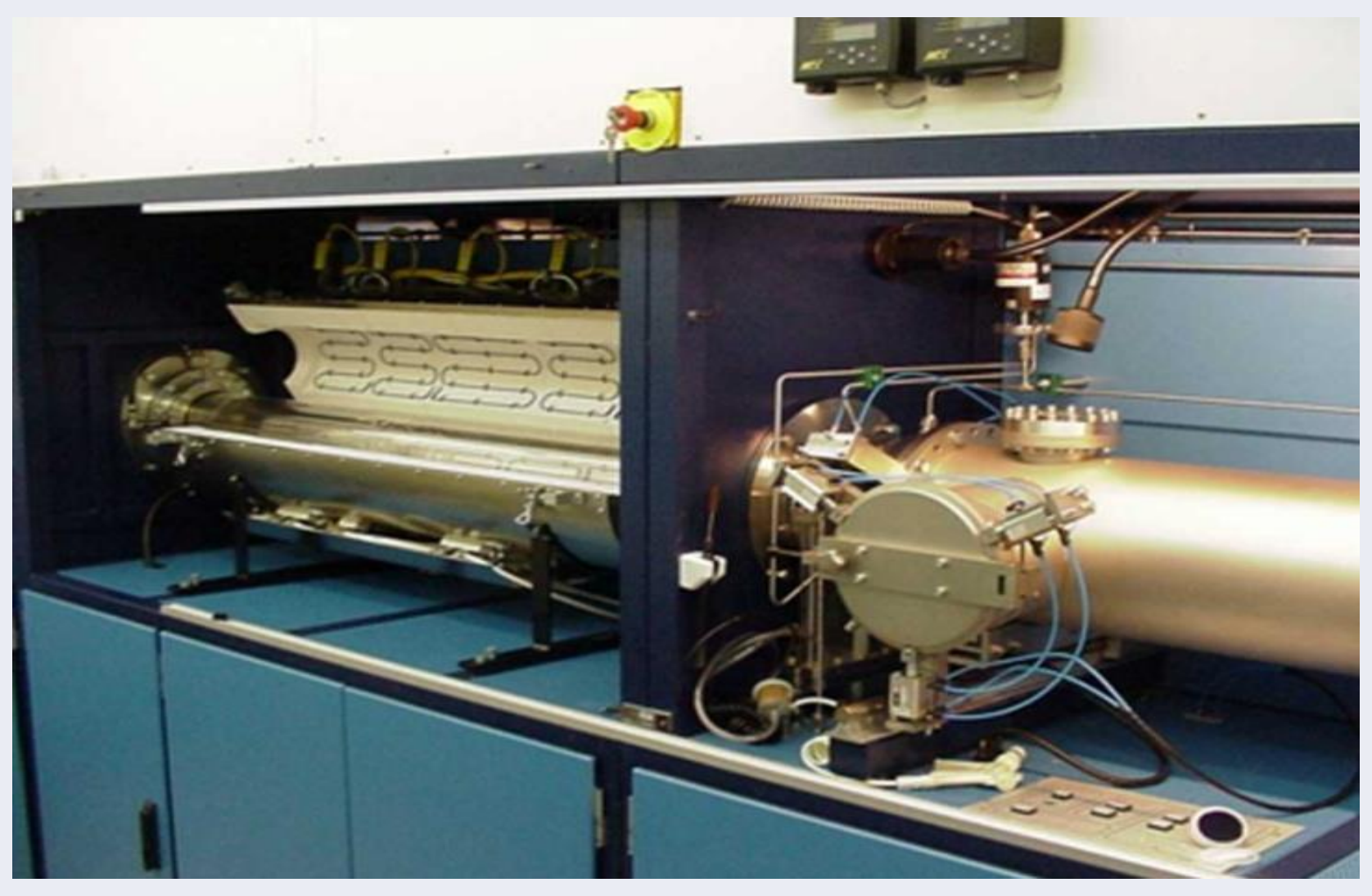
- **Aim:** Grow thick layers of orientation patterned (OP) GaP on OP-GaAs template
- **Why?:** To enable quasi phase matched structures for mid-IR and THz generation
- **How?:** Use hydride vapour phase epitaxy, an enabling technology for growing thick layers
- **Crucial issue:** Vertical domain boundaries of OP-GaP on OP-GaAs despite 3.6% lattice mismatch
- **Achieved:** + Ca 50 µm thick near vertical domains of OP-GaP on OP-GaAs
  + THz range properties of planar GaP on GaAs substrate characterized by THz time-domain spectroscopy (TDS)

Experimental

Hydride vapor phase epitaxy (HVPE)

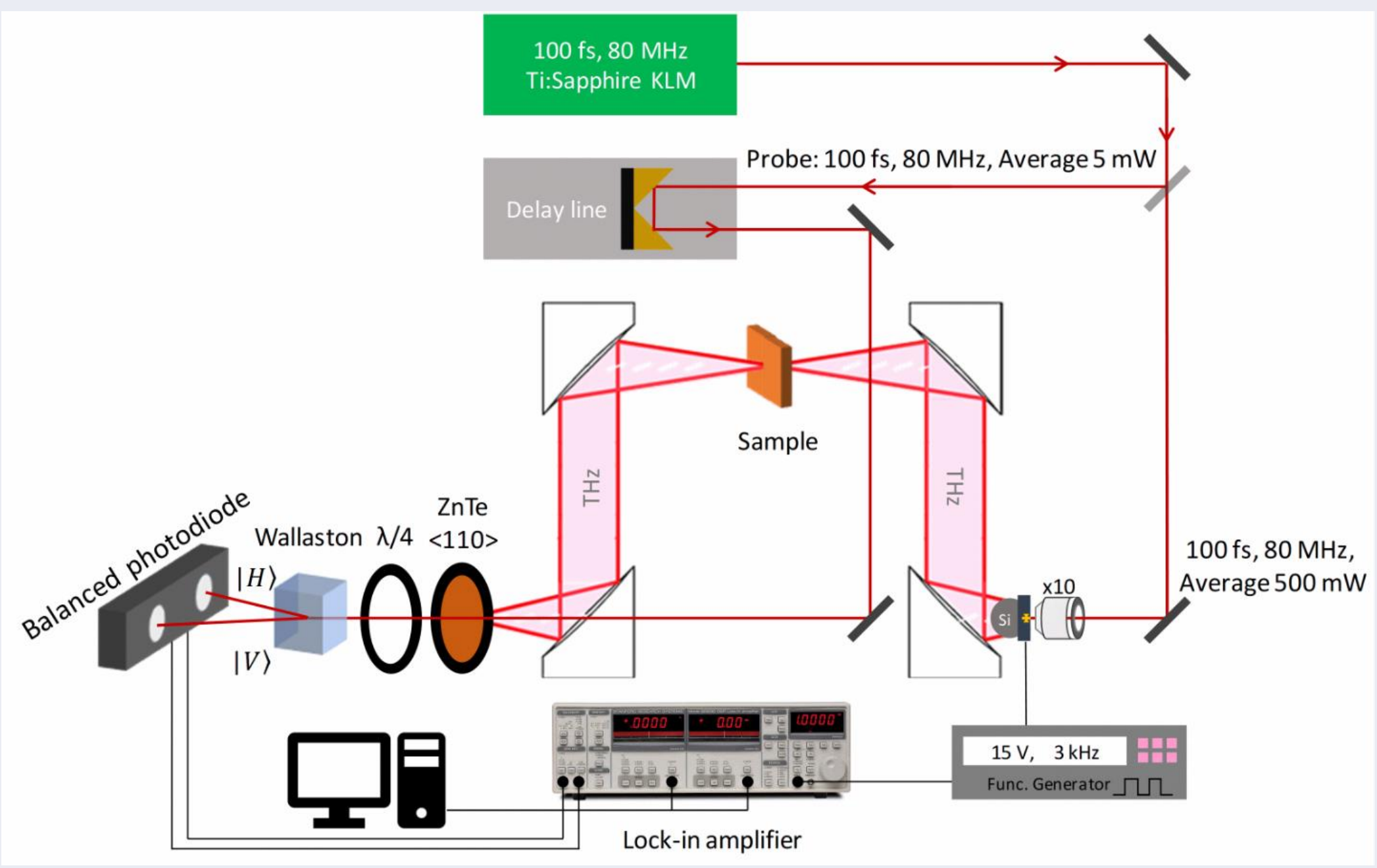
- Near-equilibrium operating conditions
- High growth rates
- Highly selective growth
- Orientation dependent growth – control over domain shapes
- Low cost metallic precursors
- Reactor pressure: 20 mbar
- Temperature: 710 ^{o}C
- Gas flows: PH_3: 25-100 sccm and GaCl: 5-25 sccm



AIXTRON LP-HVPE

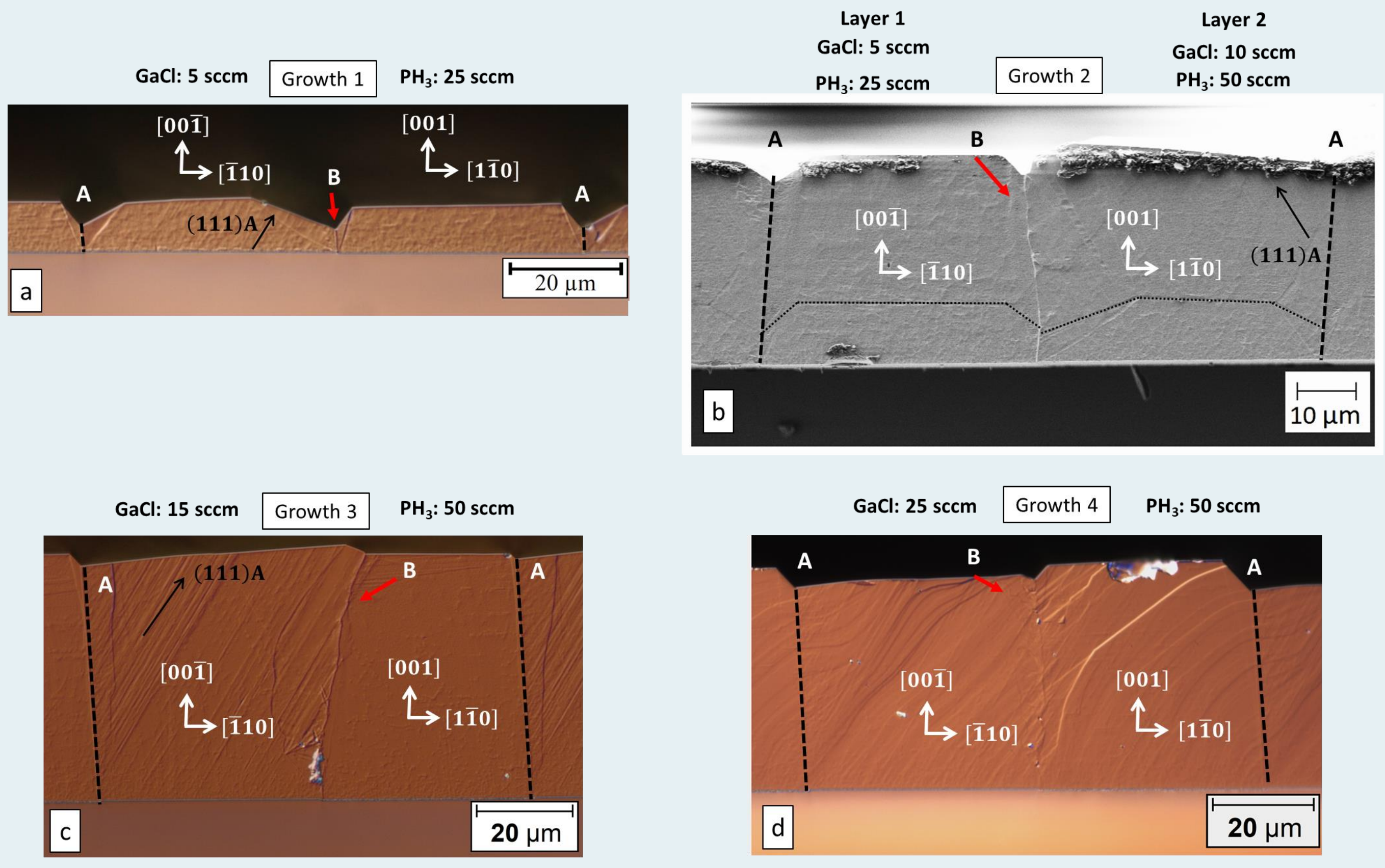
THz-Time domain spectroscopy (THz-TDS)

- Non-contact transmission measurement (through substrate)
- Contribution from the layer isolated by comparing a measurement of a bare GaAs substrate as a reference.
- 100 fs, 12 nJ pulses with a 80 MHz repetition rate



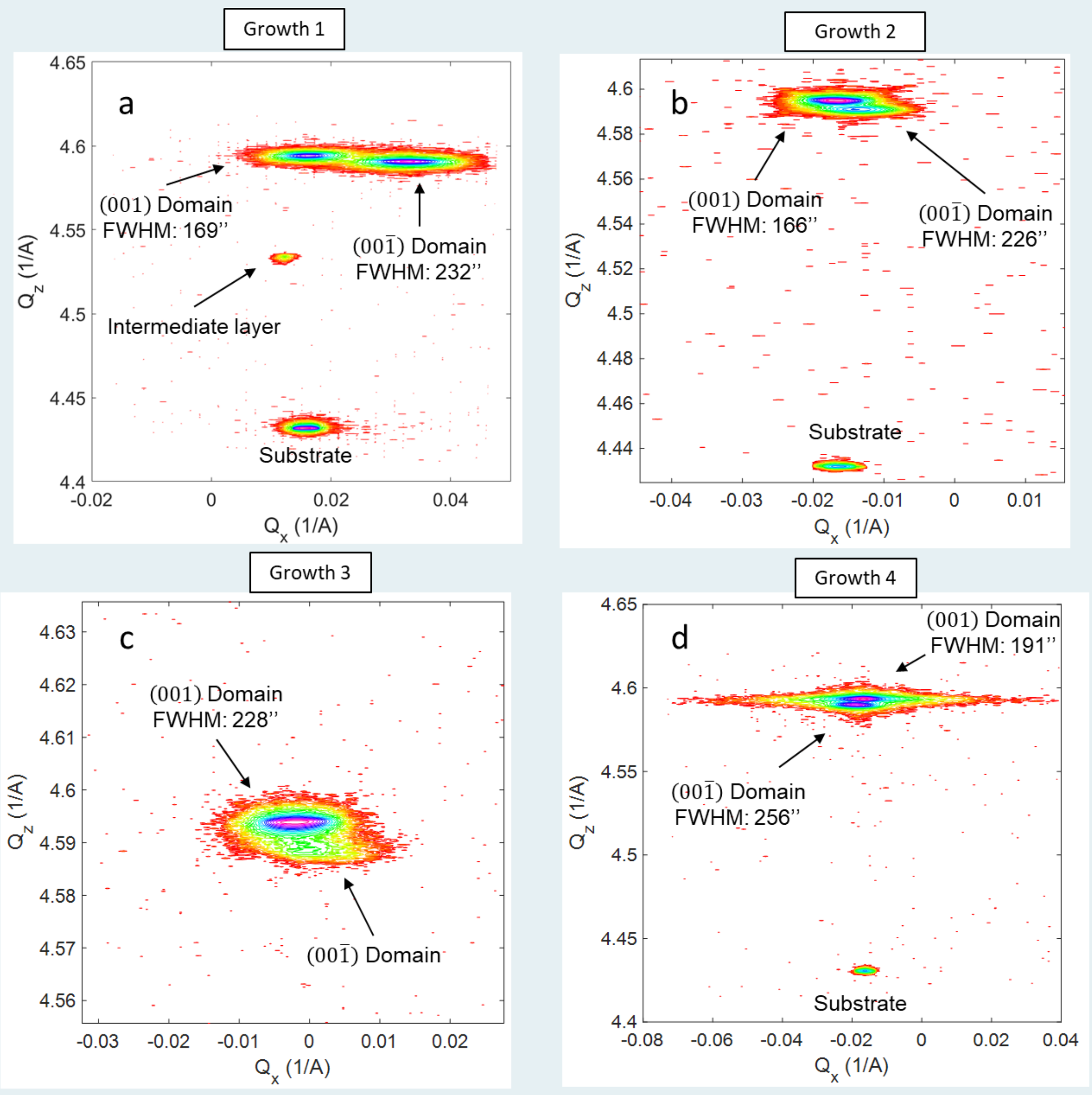
THZ-TDS SETUP

Results and Discussion



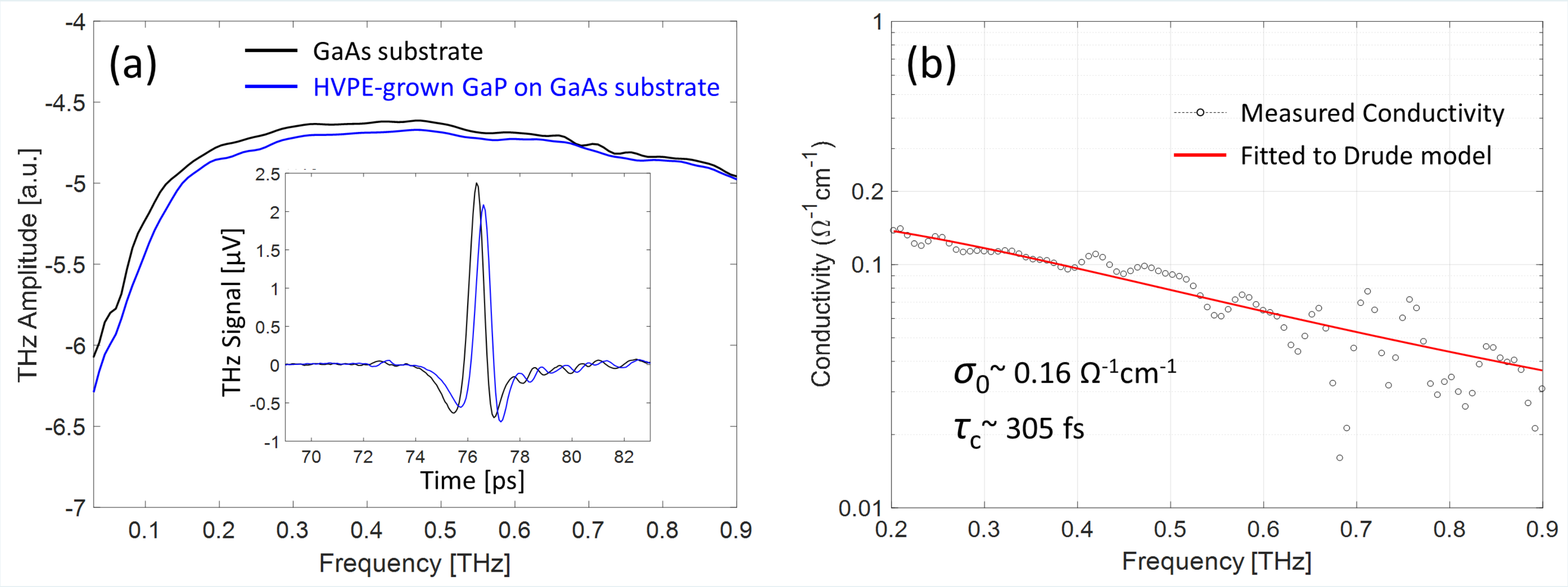
Cross-sectional Nomarski microscopy (a, c, d) and SEM (b) images of OP-GaP grown on OP-GaAs templates with different precursor flows.

- Growth 2 is performed in two steps to improve the growth rate of growth 1 while maintaining vertical domain boundaries.
- Threading dislocations (black arrows in (a-c)) suppressed by high GaCl flow in (d), resulting in vertical type B domain boundaries (red arrows).



High-resolution X-ray diffraction reciprocal lattice maps of the OP-GaP layers grown on GaAs.

- Adding a layer with high precursor gas flows on growth 1 (see a) to improve the growth rate leads to degradation of the $(00\bar{1})$ domain in growth 2 (see b) => lower intensity
- Increasing the GaCl from 15 sccm (growth 3) to 25 sccm (growth 4) crystalline quality improves for both the (001) and $(00\bar{1})$ domains (see c and d).



Measurement of conductivity of GaP using THz time-domain Spectroscopy.

(a) Comparison between THz transmission spectra for only semi-insulating GaAs substrate (reference, black line) and substrate + layer (sample, blue).

(b) Extracted conductivity of HVPE-grown GaP layer in the THz range and fitted to Drude model. A DC conductivity of 0.16 $\Omega^{-1}cm^{-1}$ is obtained, which agrees with Hall measurements!

Conclusion

- OP-GaP grown on OP-GaAs templates by direct heteroepitaxy despite 3.6% lattice mismatch
- Vertical domain boundaries achieved by optimizing the precursor flows, mitigating the effects of threading dislocations.
- Crystalline quality of the OP-GaP layers also improved by optimizing the precursor flows
- THz TDS used to characterize HVPE grown GaP on GaAs in the 0.2 – 0.9 THz range yielding a conductivity similar to that from independent Hall measurements
- OP-GaP heteroepitaxially grown on OP-GaAs templates is a promising approach for quasi-phase-matching schemes.

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