Spectroscopic Ellipsometry of Epitaxially Grown InAs/GaInSb Quantum Well Topological Insulators

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Tufts Epitaxial Core Facility (TECF)
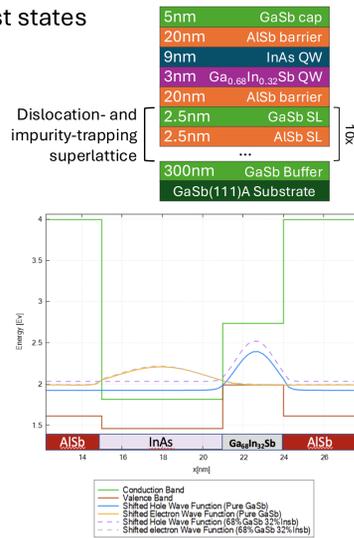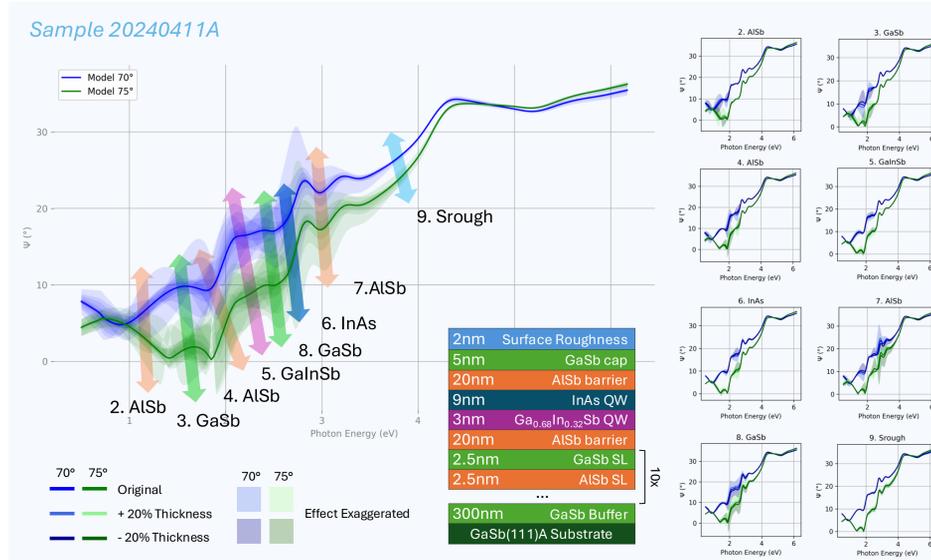
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1. Introduction

- Topological Insulators (TIs) exhibit topologically protected edge states, and are of great research interest for a range of applications
- However, existing TIs like Bi_2Se_3 require specific material platforms that limit their applicability and configurability
- Quantum well (QW)-based TIs enable precise tuning of electron and hole energies and can be built on conventional III-V platforms
- Experimental evidence of topological states has already been demonstrated in InAs/GaSb QWs[1]; simulations show alternative structures may produce more robust states
- However, device fabrication by MBE may introduce defects that affect the topological state
- Layer thickness control is key. Monolayer scale errors can induce state changes
- Spectroscopic ellipsometry: established, low cost, non-destructive method measuring layer thicknesses within samples
- We investigated several methods using ellipsometry data to determine the quality of our MBE-grown samples

5nm	GaSb cap
20nm	AlSb barrier
9nm	InAs QW
3nm	$Ga_{0.68}In_{0.32}Sb$ QW
20nm	AlSb barrier
2.5nm	GaSb SL
2.5nm	AlSb SL

Dislocation- and impurity-trapping superlattice (10x)

| 300nm | GaSb Buffer |
| | GaSb(111)A Substrate |

2. Experimental Details

- Experiments were performed using a J.A. Woollam VASE UV-NIR Spectroscopic Ellipsometer
- Scans were collected at 70° and 75° incidence angles, spanning photon energies from 0.5 eV to 6.2 eV in 0.025 eV steps

3. GaInSb Optical Characterization

- The $Ga_xIn_{1-x}Sb$ QW hosts the quantum confined hole states
- The optical characteristics of $Ga_xIn_{1-x}Sb$ have yet to be tabulated in literature, so we collected them ourselves

GaInSb Calibration Sample

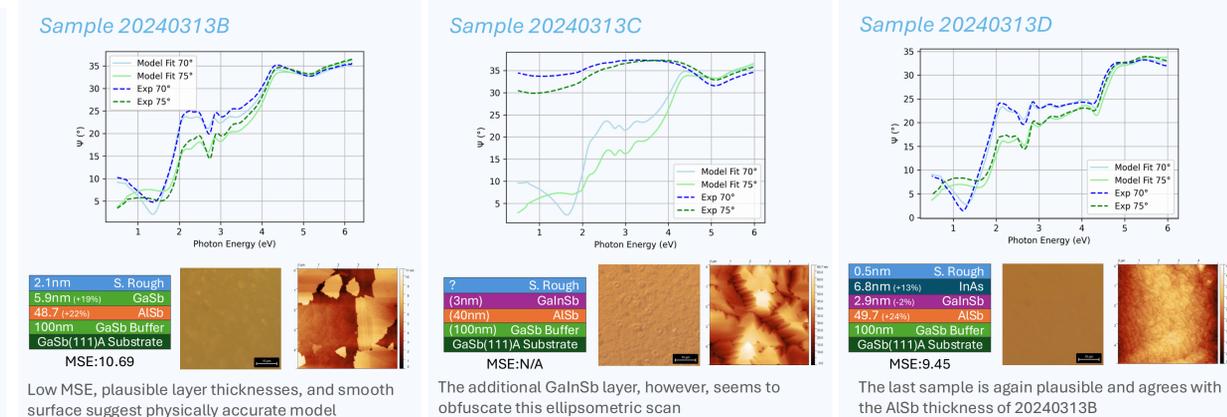| 2.3nm | Surface roughness |
| 10nm | $Ga_{0.68}In_{0.32}Sb$ |
| | GaSb(111)A Substrate |

MSE: 4.20

4. Individual Layer Effects

- Model individual effects of changing each layer thickness to A) verify that each layer is distinguishable and B) to serve as a guide for peak matching which can be more effective for determining thicknesses than minimizing mean squared error (MSE)

Sample 20240411A

2nm	Surface Roughness
5nm	GaSb cap
20nm	AlSb barrier
9nm	InAs QW
3nm	$Ga_{0.68}In_{0.32}Sb$ QW
20nm	AlSb barrier
2.5nm	GaSb SL
2.5nm	AlSb SL

(10x)

| 300nm | GaSb Buffer |
| | GaSb(111)A Substrate |

70° 75° Original
70° 75° + 20% Thickness
70° 75° - 20% Thickness
Effect Exaggerated

- Knowledge of which spectral features come from which layers helps improve fitting with the ellipsometry model

5. Constrained Fitting

- Growth rate of III-Vs are determined by group III element
- Fix ratios of layers with proportional growth rates to limit number of unknowns

Sample 20231228B

Unconstrained
3.8nm (-23%)	GaSb cap
53.5nm (+34%)	AlSb B.
15.5nm (+73%)	InAs QW
7.9nm (+166%)	GaInSb QW
44.5nm (+11%)	AlSb B.
4.7nm (+58%)	AlSb SL
2.8nm (+12%)	GaSb SL
300nm	GaSb Buffer
	GaSb(111)A Substrate

MSE: 21.36

Constrained
4.4nm (-12%)	GaSb cap
53.5nm (+34%)	AlSb B.
18.6nm (+107%)	InAs QW
5.3nm (+76%)	GaInSb QW
44.8nm (+34%)	AlSb B.
4.0nm (+34%)	AlSb SL
2.6nm (-12%)	GaSb SL
300nm	GaSb Buffer
	GaSb(111)A Substrate

MSE: 23.85

Similar fits between the unconstrained and constrained models (and the overall low MSE) suggest that the resulting model is physically accurate

Sample 2024320A

Unconstrained
1.7nm	S. Rough
2.4nm (-51%)	GaSb cap
18.9nm (-16%)	AlSb B.
0.0nm (-100%)	InAs QW
4.7nm (+58%)	GaInSb QW
20.9nm (+0%)	AlSb B.
3.3nm (+33%)	AlSb SL
2.2nm (-10%)	GaSb SL
100nm	GaSb Buffer
	GaSb(111)A Substrate

MSE: 32.7

Constrained
1.7nm	S. Rough
4.1nm (-19%)	GaSb cap
23.5nm (+4%)	AlSb B.
2.1nm (+64%)	InAs QW
5.2nm (+73%)	GaInSb QW
20.9nm (+5%)	AlSb B.
2.6nm (+5%)	AlSb SL
2.0nm (-19%)	GaSb SL
100nm	GaSb Buffer
	GaSb(111)A Substrate

MSE: 41.6

The difference between the unconstrained and constrained sample is larger and the unconstrained model has an unphysical 0nm layer thickness, bringing less confidence to this model

6. Partial Structures

- Another method of limiting the number of unknowns is by breaking apart the structure into several samples and growing each sample with one additional layer
- As long as growth conditions are kept consistent between samples, each sample should differ by a single layer corresponding to a single unknown

Sample 20240313B
2.1nm	S. Rough
5.9nm (+19%)	GaSb
48.7 (+22%)	AlSb
100nm	GaSb Buffer
	GaSb(111)A Substrate

MSE:10.69

Low MSE, plausible layer thicknesses, and smooth surface suggest physically accurate model

Sample 20240313C
?	S. Rough
(3nm)	GaInSb
(40nm)	AlSb
(100nm)	GaSb Buffer
	GaSb(111)A Substrate

MSE:N/A

The additional GaInSb layer, however, seems to obfuscate this ellipsometric scan

Sample 20240313D
0.5nm	S. Rough
6.8nm (+13%)	InAs
2.9nm (-2%)	GaInSb
49.7 (+24%)	AlSb
100nm	GaSb Buffer
	GaSb(111)A Substrate

MSE:9.45

The last sample is again plausible and agrees with the AlSb thickness of 20240313B

- High roughness on the GaInSb surface precluded fixing that samples thickness, but the agreement between the AlSb layers in the first and third sample suggests future potential for this method

7. AFM & Nomarski Comparison

- Given the correlation between surface roughness and goodness of fit, we performed Nomarski and AFM on the sample with the best fit.

Sample 20231228A
3.8nm	S. Rough
3.9nm (-22%)	GaSb cap
54.8nm (+37%)	AlSb B.
12.7nm (+41%)	InAs QW
6.7nm (+125%)	GaInSb QW
54.8nm (+37%)	AlSb B.
4.11nm (+37%)	AlSb SL
2.3nm (-22%)	GaSb SL
300nm	GaSb Buffer
	GaSb(111)A Substrate

MSE: 32.30

- Nomarski and AFM suggest that the surface is relatively smooth, with peaks of about 5nm.
- Since this is much lower than refractive index adjusted wavelengths, it is reasonable for such roughness to not appear on the ellipsometry scan

8. Conclusion

Spectroscopic ellipsometry can provide insight into complex, many layered QW-based TI structures especially when augmented with constraints, though alternate methods are necessary for finer details
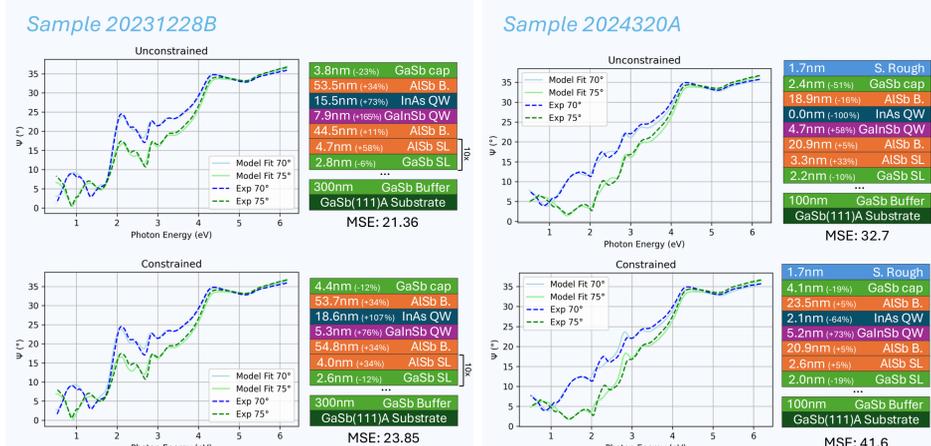
References

[1] S. Schmid, M. Meyer, F. Jabeen, G. Bastard, F. Hartmann, and S. Höfling, "Exploring the phase diagram of InAs/GaSb/InAs trilayer quantum wells," Phys. Rev. B **105**, 155304 (2022).