Semiconductor Supermirrors: When planar wafer bonding just isn’t hard enough...

September 5, 2019
Basic Mirror and Optical Coating Background

- Two main classes of thin-film reflective optical coatings
  1. simple metallic mirrors: single or protected Ag, Al, or Au layer
  2. interference coatings: alternating transparent dielectric films
- Properly designed interference coatings exhibit lower losses
Interference leads to rapid decay of optical field in Bragg reflector

Three loss mechanisms:

i) transmission
ii) absorption
iii) scatter

- Alternating layers of high / low index quarter-wave thickness thin films
  - at Bragg wavelength internal reflections add in phase, max. reflectivity
- Individual layers are transparent, yielding low absorption reflectors
  - losses ultimately constrained by layer design, impurities, and roughness
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Timeline of Competing Coating Technologies

Current amorphous coatings

- 1857: Arc Evaporation
- 1907: E-beam Evaporation
- 1939: Magnetron Sputtering
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Fluctuating mirror
Brownian noise
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Semiconductor Supermirrors

- 2012: Crystalline Coatings
Physical Vapor Deposition of Amorphous Coatings

- Multilayer of amorphous thin films via ion beam sputtering (IBS)
- Phenomenal optical properties: high R, low absorption and scatter
- Flexible choice of substrates assuming excellent surface quality
  - super-polished SiO₂, Si, ULE, sapphire, etc.

State-of-the-art multilayer mirrors: ion-beam sputtered Ta₂O₅/SiO₂
• First demonstrated in 1975
  • interference coatings by van der Ziel and Ilegems, Bell Labs
• Primary application: VCSELs
  • K. Iga’s group (Tokyo) and Bell Labs (Jewell et al.)
  • VCSELs consist of high-reflectivity mirrors surrounding a semiconductor microcavity
  • global VCSEL market estimated to be worth $3.6B by Q4 2020
• Lattice matching constraints limit substrate selection
  • monocrystalline multilayers require a crystalline template

Large-aperture linear VCSEL array, Aerius Photonics, LLC (FLIR Electro-Optical Components)
Lattice Matched Epitaxial Multilayers

The graph shows the bandgap energy $E_g$ (eV) as a function of the lattice constant $a_0$ (Å). Different materials are plotted, including AlP, GaP, AlAs, AlSb, GaAs, InP, GaSb, InAs, InSb, AlP, and GaAs. The graph also indicates direct and indirect gap regions.

- **Bandgap energy $E_g$ (eV)**: The y-axis represents the bandgap energy in electron volts (eV).
- **Lattice constant $a_0$ (Å)**: The x-axis represents the lattice constant in ångströms (Å).
- **Wavelength $\lambda$ (μm)**: The right y-axis represents the wavelength in micrometers (μm).

The graph includes both direct gap (solid lines) and indirect gap (dashed lines) for each material, illustrating the variation in bandgap energy with lattice constant.
- AlGaAs multilayer with varying Al content for index contrast
  - high index layers consist of binary GaAs thin films
  - 8% Ga incorporated in low index AlGaAs layers to slow oxidation in ambient

- Epitaxy generates DBRs with low defect density, high purity, and excellent thickness control
  - limited by lattice matching...

- Leverage transfer & direct bonding to overcome this
  - commonly employed process, e.g. for manufacturing SOI (silicon-on-insulator) wafers up to 45 cm in diameter
Epitaxial Bragg Mirrors

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Merging Semiconductor Manufacturing with Bulk Optics

Direct bonding is used to attach the single-crystal interference coating to the final optical substrate. Monocrystalline GaAs/AlGaAs heterostructures grown on GaAs wafers by molecular beam epitaxy. Using semiconductor manufacturing techniques, the multilayer is extracted from the original GaAs wafer.
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Epitaxial multilayers on arbitrary substrates.
Physical vapor deposition can be realized on multiple substrates simultaneously.

Wafer-scale batch fabrication enables the generation of many GaAs/AlGaAs mirror disks, though bonding remains a serial process.
• Crystalline coatings entail a unique manufacturing process
  • we purchase base GaAs wafers from an external supplier
  • epitaxial growth of a custom designed multilayer w/ MBE
  • using a proprietary process we remove and directly bond the
    single-crystal multilayer to a super-polished substrate
Epitaxial Growth Options

Molecular beam epitaxy

- MBE enables low background doping, minimizing absorption
- Oval defects in GaAs (spitting Ga source) are a persistent problem

Metal organic chemical vapor deposition

- C incorporation in AlGaAs is a major barrier to achieving low absorption
- An optimized MOCVD process can generate defect free films
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Substrate-Transfer Process: Step 1, Litho and Etch

150 mm Ø
Step 2: Die Singulation via Lapping

- Contact lithography is used to define the coating geometry
  - a non-selective wet etch ($\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$) transfers this pattern into the DBR and partially into the GaAs wafer

- A second mask is used to define a slightly larger mesa
  - the same chemistry is used to deep etch (150-250 μm) into the substrate (which is typically 675 μm thick)

- Lapping is used to thin the underlying wafer to ~100 μm
  - singulated die are generated with excellent control of the lateral geometry
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Step 3: Direct Bonding of Cleaned and Activated Components

24 mm

48 mm

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- **Ø48 mm, thinned (100 µm) mirror disc**
- **NO adhesives, solders, or intermediate layers**
- **Ø48 mm, 5 m ROC, 24 mm thick fused-silica substrate**
Steps 4 and 5: Substrate Removal and Final Cleaning

• High optical performance realized with acceptable yield
  • typical crystalline coatings are 0.5-1 inch in diameter
  • maximum delivered coating diameter to date is 3” / 76.2 mm
  • we can successfully transfer epilayers onto surfaces w/ a 10-cm ROC
Semiconductor-based optical interference coatings transferred to alternative substrates (SiO₂, Si, SiC, Al₂O₃, YAG, YVO₄, diamond, etc.)

- 10x LOWER Brownian noise
- ULTRAPRECISE measurements of space and time

- 10x LOWER mid-IR absorption
- HIGH RESOLUTION trace gas sensing

- 30x LOWER thermal resistivity
- THERMAL MANAGEMENT in industrial lasers
Based on our unique advantages we have developed 3 products and 1 service line:

- **xtal stable™**: Ultrastable laser resonators for metrology and navigation
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Custom Optical Reference Cavities and Low-Noise Optics

- Dozens of cavities & mirrors deployed on SiO$_2$, Si, and Al$_2$O$_3$ subs.
- Mirror diameters of 0.5” to 2” and spacer lengths up to 30 cm
- Wavelengths from ~1000 nm to 1600 nm, RT and cryo (4-124 K)
  - excess losses < 3 ppm measured via ringdown, reflectivity > 99.999%
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“All Crystalline” Cryogenic Cavity

transmission $\approx 5 \text{ ppm}$

scatter + abs $\approx 4 \text{ ppm}$

45.5 period GaAs/AlGaAs

$\tau = 32.3 \mu$s

Finesse $= 3.6 \times 10^5$

transmission $\approx 5 \text{ ppm}$

scatter + abs $\approx 4 \text{ ppm}$
Δf/f \sim 1 \times 10^{-17}

45.5 period
GaAs/AlGaAs

\textit{All Crystalline} Cryogenic Cavity

\textbf{JILA NISTCQ}

\textbf{PTB}

\textbf{CMS}
• Finesse of nearly 400,000 @ Si CTE zero-crossing temp. (~123 K)
  • total losses (T+S+A) of 8 ppm at center wavelength of 1542 nm
  • target transmission of 5±1 ppm realized, excess losses (S+A) < 3 ppm
Ultrastable cavities now available in turn-key low-noise lasers from Menlo Systems
- the first rack-mounted lasers with a frequency instability $\sim 10^{-16}$ (<100 mHz linewidth)
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Substrate-transferred crystalline coatings exhibit excellent optical and thermo-mechanical quality

- Elastic loss reduction of $10-100 \times$ over amorphous films
  - AlGaAs room temperature mechanical Q $\approx 4 \times 10^4$ ($\phi_{RT} \approx 2 \times 10^{-5}$)
  - AlGaAs cryogenic performance: Q $> 1 \times 10^5$ ($\phi_{min} \approx 4.5 \times 10^{-6}$)

- Optical losses on par-with with the best IBS coatings
  - absorption $< 1$ ppm via PCI in the NIR, scatter loss $< 3$ ppm
  - cavity finesse $> 600,000$ ($R > 99.9995\%$) measured at 1550 nm
  - exceptional MIR performance, ppm-level losses to 5+ μm

- High conductivity (30$\perp$, 70$\parallel$ Wm$^{-1}$K$^{-1}$), promising LIDT
  - measured CW $> 50$ MW/cm$^2$ without damage (1064 nm)
  - typical LIDT values for $\sim$1 μm & ns pulses: 2-8 J/cm$^2$
    ultimately limited by TPA ($\beta_{GaAs} \approx 20$ cm/GW, $E_g \approx 870$ nm)
Thank you for your attention!