Tunable VCSELs with Emission Wavelengths Below 800 nm

Technische Universität Darmstadt

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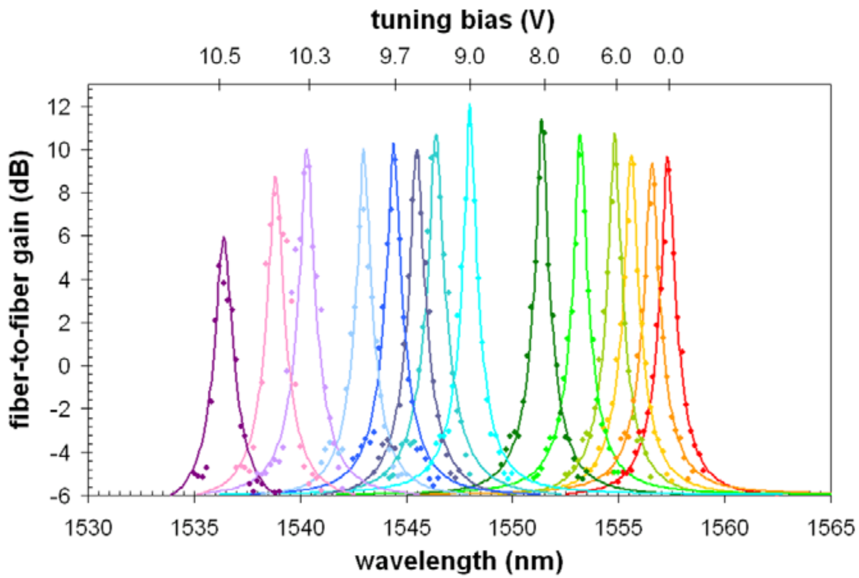
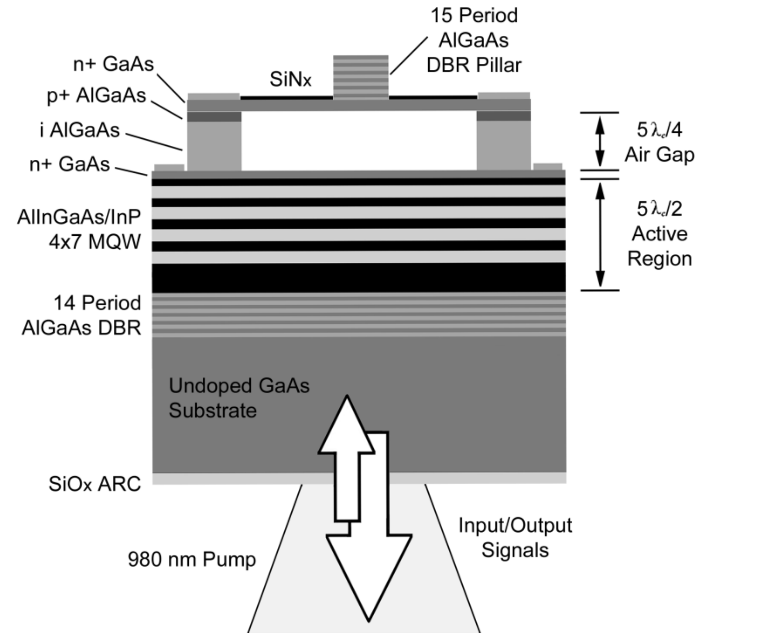
AOM
ADVANCED OPTICAL
MICROSYSTEMS

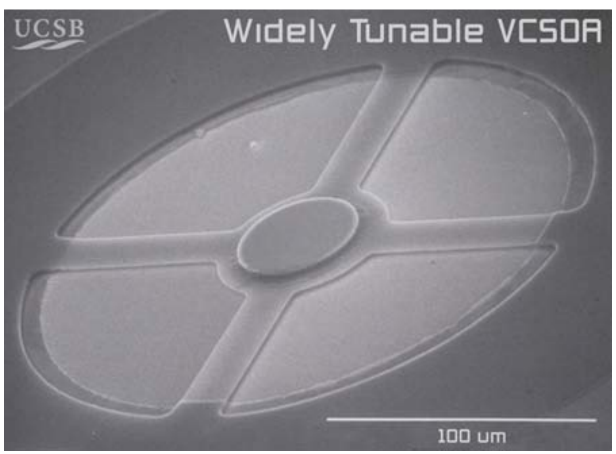
Outline

- Background work on tunable vertical-cavity SOAs
- Motivation for short-wavelength MEMS-VCSELs
- Epitaxial materials structure and device design
- Novel dry-released sacrificial α-Ge etch process
- Laser and electrostatic acuator characterization
- Future work and conclusions

MEMS-Tunable Vertical-Cavity SOAs







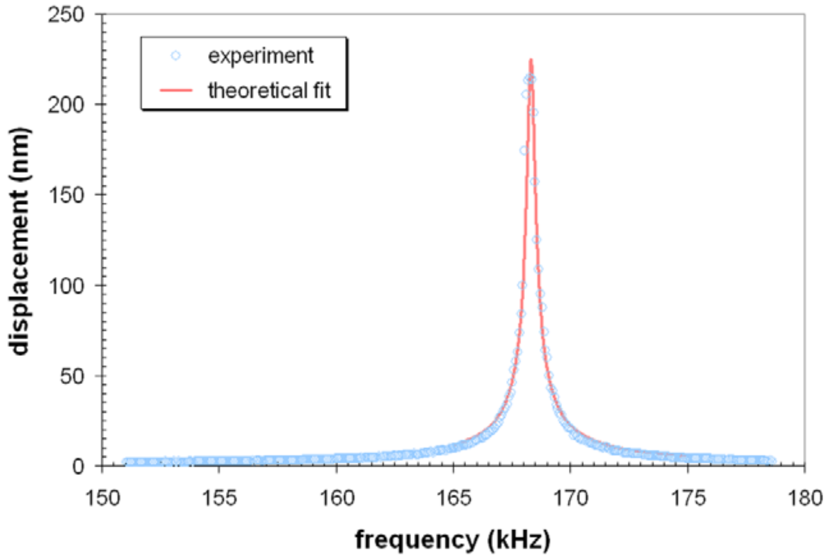
- Monolithic GaAs/InP/GaAs cavity structure
- 28 AlInGaAs QWs, epitaxial MEMS DBR
- 980-nm EDFA pump for excitation

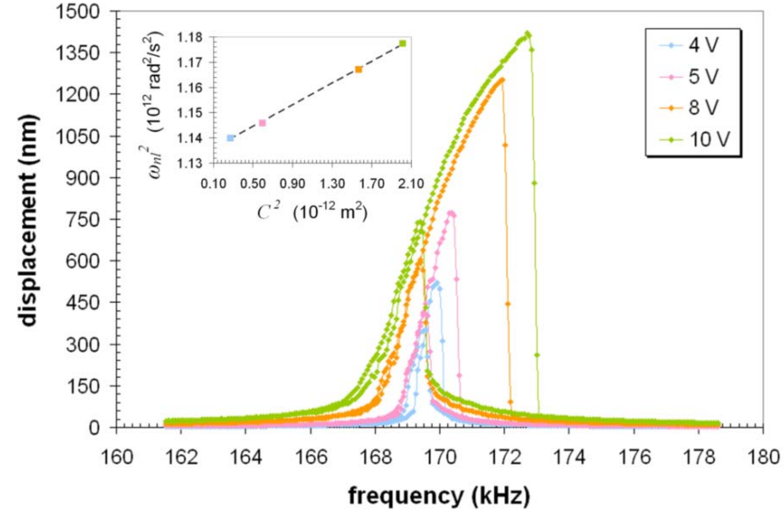
State of the art VCSOA performance:

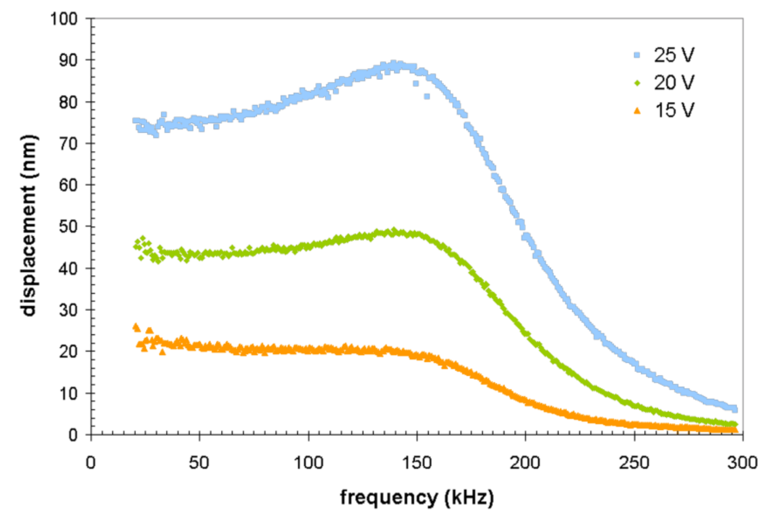
- ~10 dB fiber-to-fiber gain over 21 nm
- SM-fiber-coupled gain of 11.2 dB (18.2 dB on chip)
- Saturation output power of -1.36 dBm

G. D. Cole, E. S. Bjorlin, C. S. Wang, N. C. MacDonald, and J. E. Bowers, "Widely tunable bottom-emitting vertical-cavity SOAs," *IEEE Photonics Technology Letters*, vol. 17, no. 12, Dec. 2005, pp. 2526–2528.

MEMS-Tunable Vertical-Cavity SOAs







MEMS characterization via LDV:

- Simple harmonic response for small signal excitation in vacuum
- Duffing response for large deflection
- Atmospheric response is highly damped
  - Q of 1.2, response time of 6 μs

G. D. Cole, J. E. Bowers, K. L. Turner, and N. C. MacDonald, “Dynamic characterization of MEMS-tunable vertical-cavity SOAs” *IEEE/LEOS Optical MEMS 2005, Oulu, Finland, 1–4 Aug. 2005, paper F4.*

Motivation: Short-λ MEMS-VCSELs

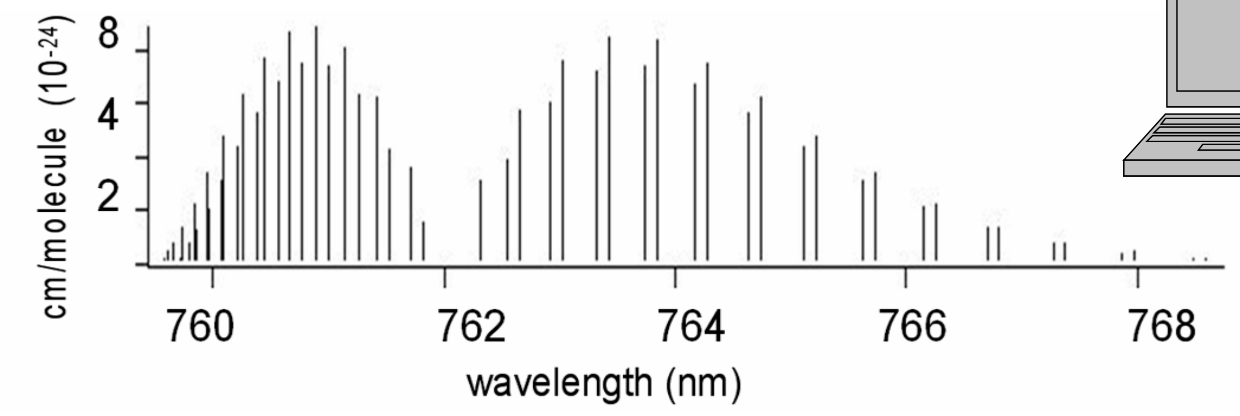
Advantages of VCSELs for sensing applications

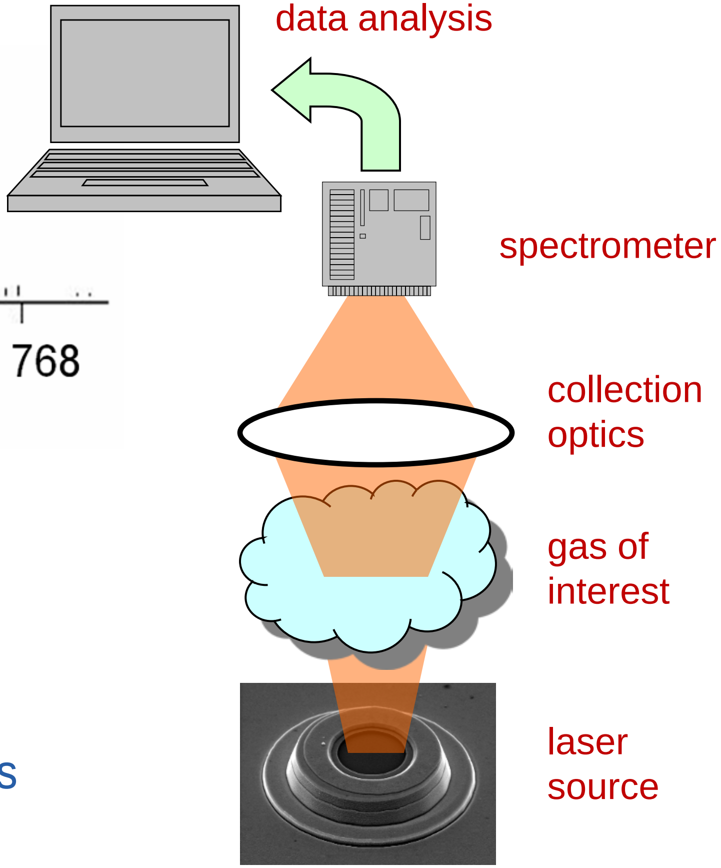
- 2-D arrays, on-chip testing, potential for low cost manufacturing
- Compact device size and low power consumption
- Many gases of interest have absorption overtones in the NIR

The next step: MEMS-tunable surface-emitting lasers

- Simple tuning control eases tolerances on initial emission wavelength
- Micromechanical integration enables rapid broadband tuning
  - Electrostatic actuation for MHz scan rates
  - Wide tuning range for interrogation of heterogeneous mixtures

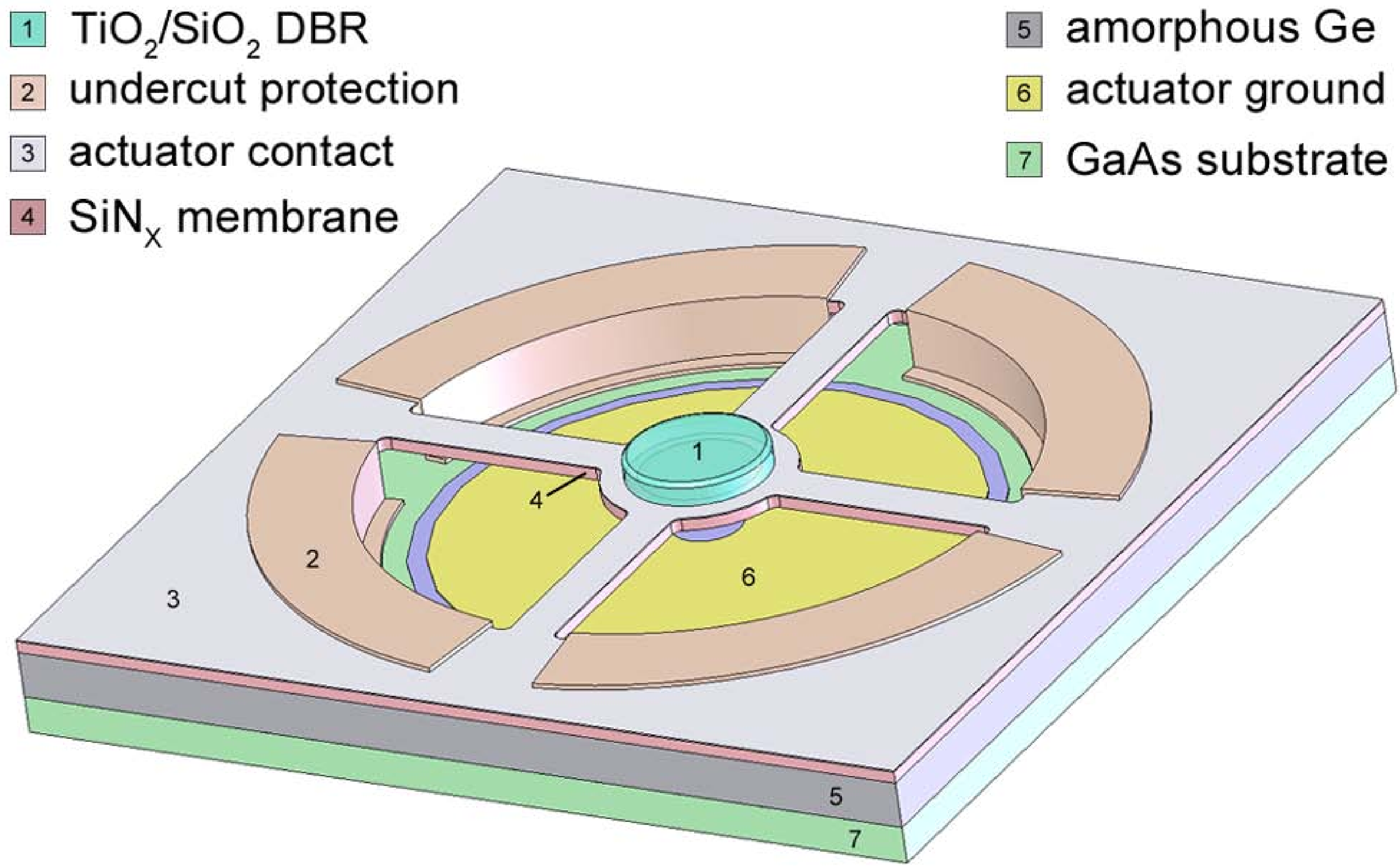
O_2 Sensing: Fast-Scanning Source





- Tunable VCSEL as a scanning laser source
  - target absorption overtones in the NIR
  - emission near 760 nm for O2 sensing
  - electrostatic actuation for MHz scan rates
  - interrogation of heterogeneous gas mixtures
- Relevant applications
  - industrial and automotive combustion process monitoring
  - dynamic acquisition for “real time” analysis

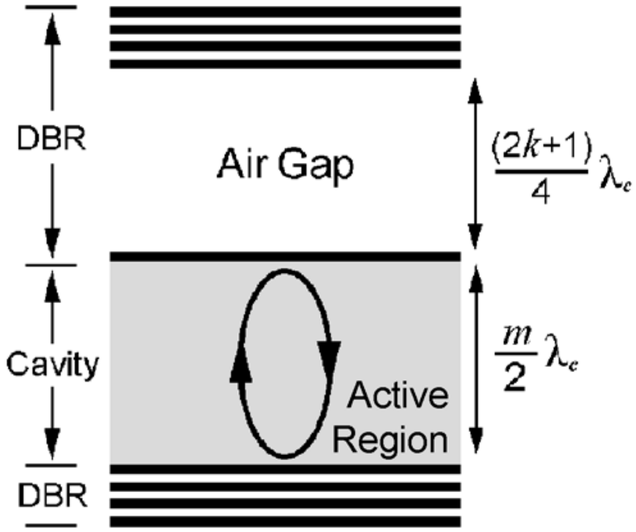
General Device Layout



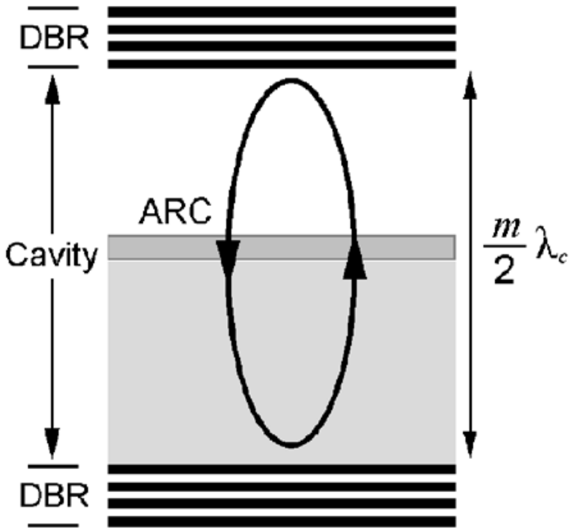
G. D. Cole, E. Behymer, T. C. Bond, and L. L. Goddard, "Short Wavelength MEMS-Tunable VCSELs," *Optics Express*, vol. 16, no. 20, pp. 16093–16103, September 2008.

Tunable Cavity Design Options

Semiconductor Coupled Cavity



Extended Cavity

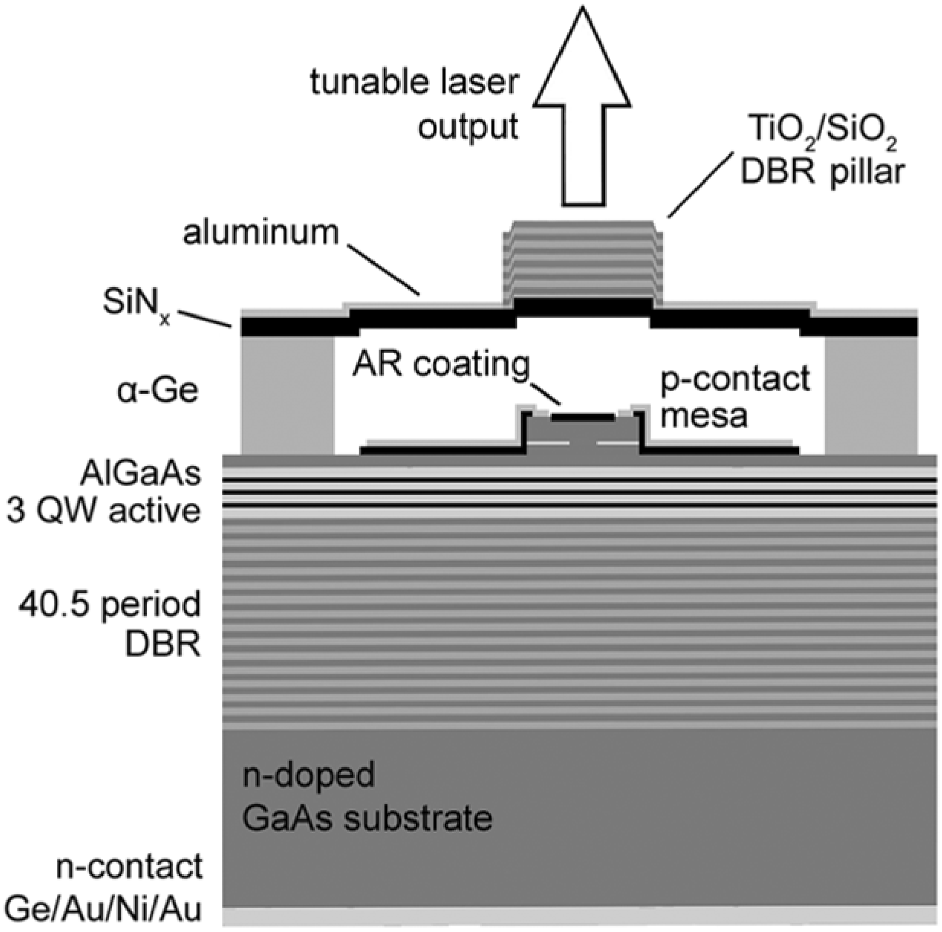


Wavelength tuning achieved by physically altering cavity length

- Suspended top mirror; remaining elements identical to fixed-λ lasers
- SCC-design allows for largest overlap with gain medium
- EC-design exhibits linear wavelength shift and constant reflectance

G. D. Cole, E. S. Björlin, Q. Chen, C.-Y. Chan, S. Wu, C. S. Wang, N. C. MacDonald, and J. E. Bowers, “MEMS-tunable vertical-cavity SOAs,” *IEEE Journal of Quantum Electronics*, vol. 41, no. 3, pp. 390–407, March 2005.

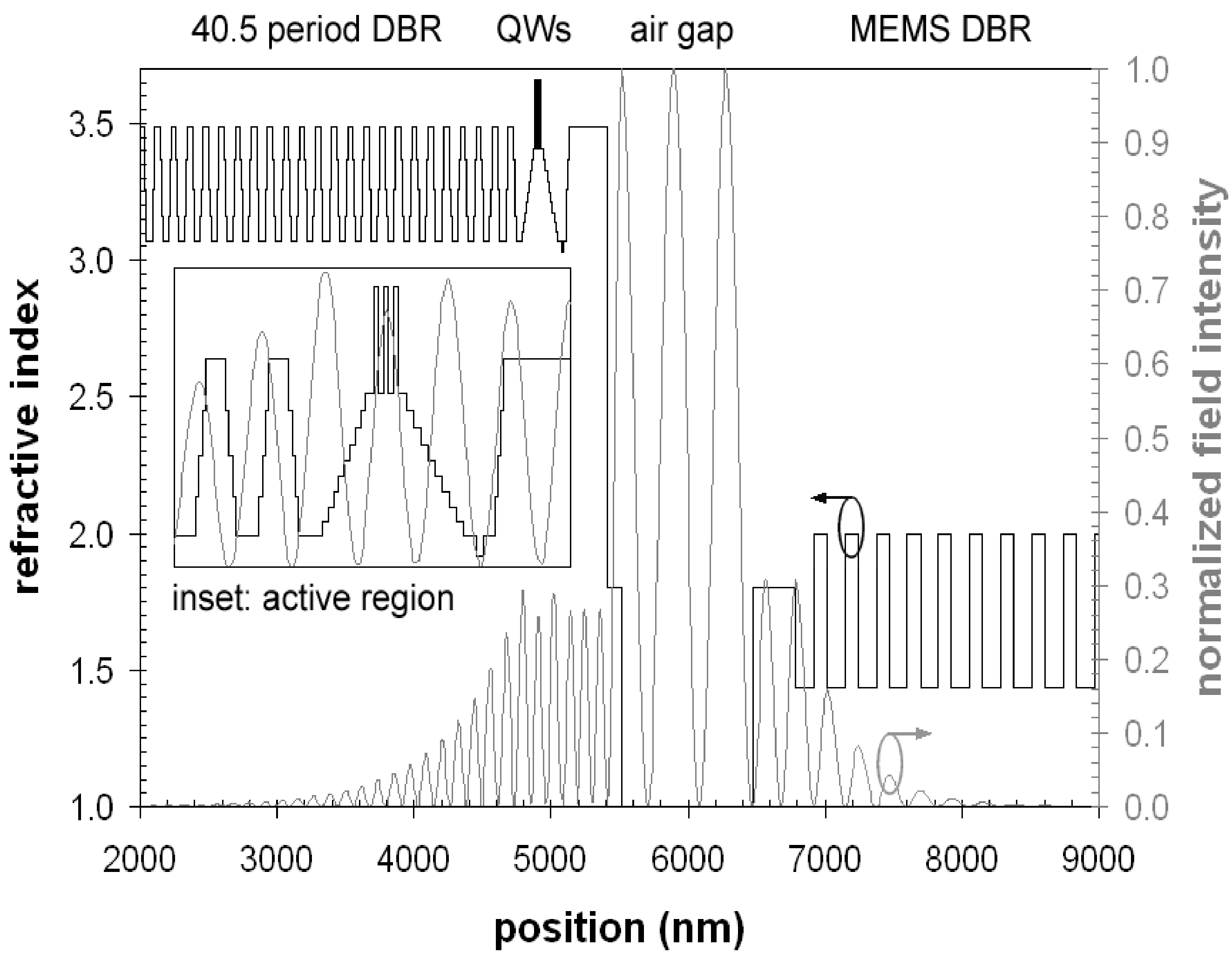
Cross-Section of Full Laser Structure



- Epitaxial structure consists solely of AlGaAs
- Linear composition grading for reduced resistance
- Lateral oxidation for carrier and optical confinement
- Intra-cavity p-contact on mesa below suspended mirror
- Electrostatic actuation of dielectric DBR for λ tuning (extended cavity design)

G. D. Cole, E. Behymer, T. C. Bond, and L. L. Goddard, "Short Wavelength MEMS-Tunable VCSELs," *Optics Express*, vol. 16, no. 20, pp. 16093–16103, September 2008.

Index Profile and Standing Wave



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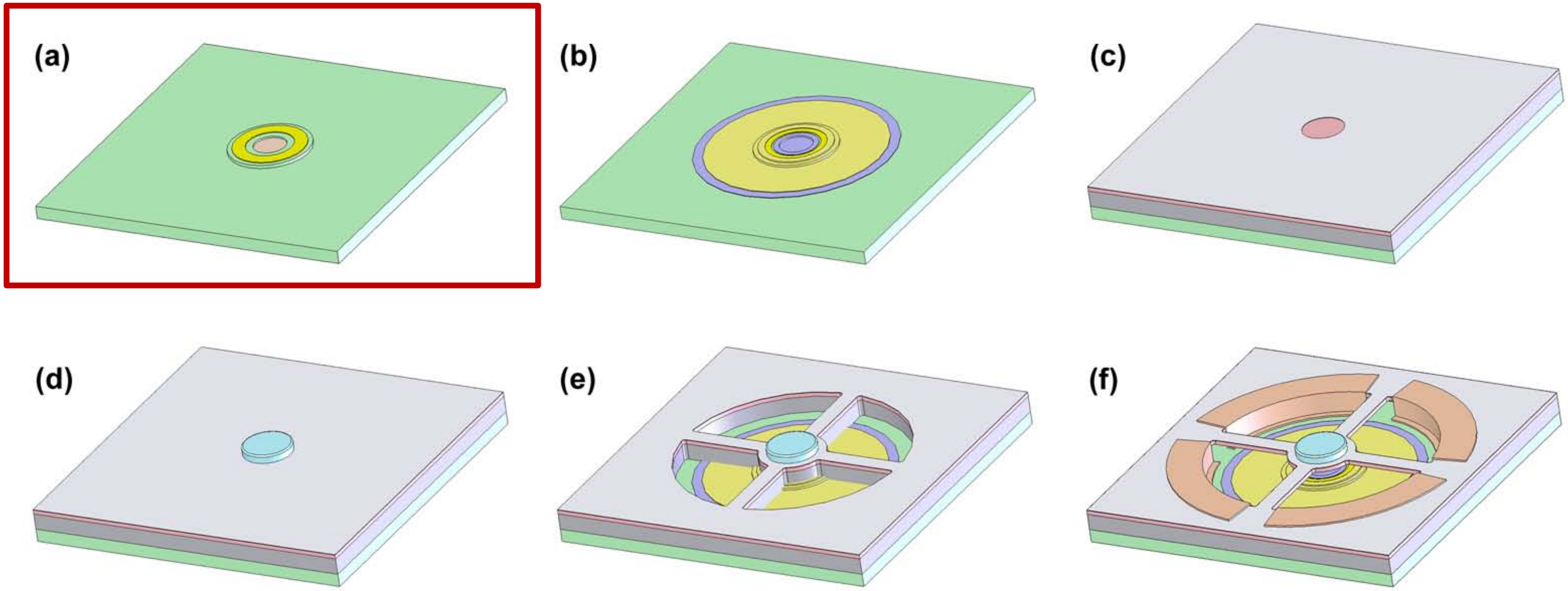
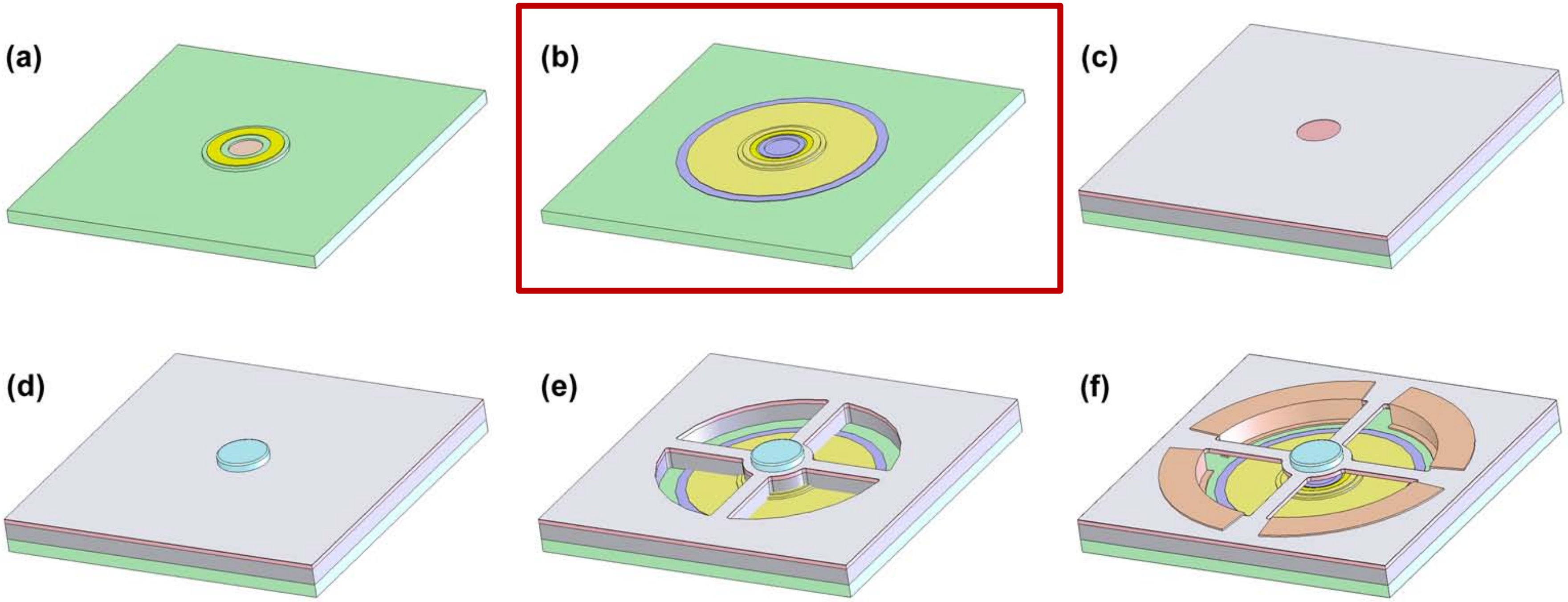
Dry Release Process Flow



a) mesa wet etch, oxidation, p-contact definition, and contact window wet etch

G. D. Cole, et al., “Fabrication of suspended dielectric mirror structures via xenon difluoride etching of an amorphous germanium sacrificial layer,” *Journal of Vacuum Science and Technology B*, vol. 26, no. 2, March/April 2008, pp. 593–597.

Dry Release Process Flow



b) Si_xN_y AR coating deposition and etch back;
Ti / Au p-contact pad liftoff

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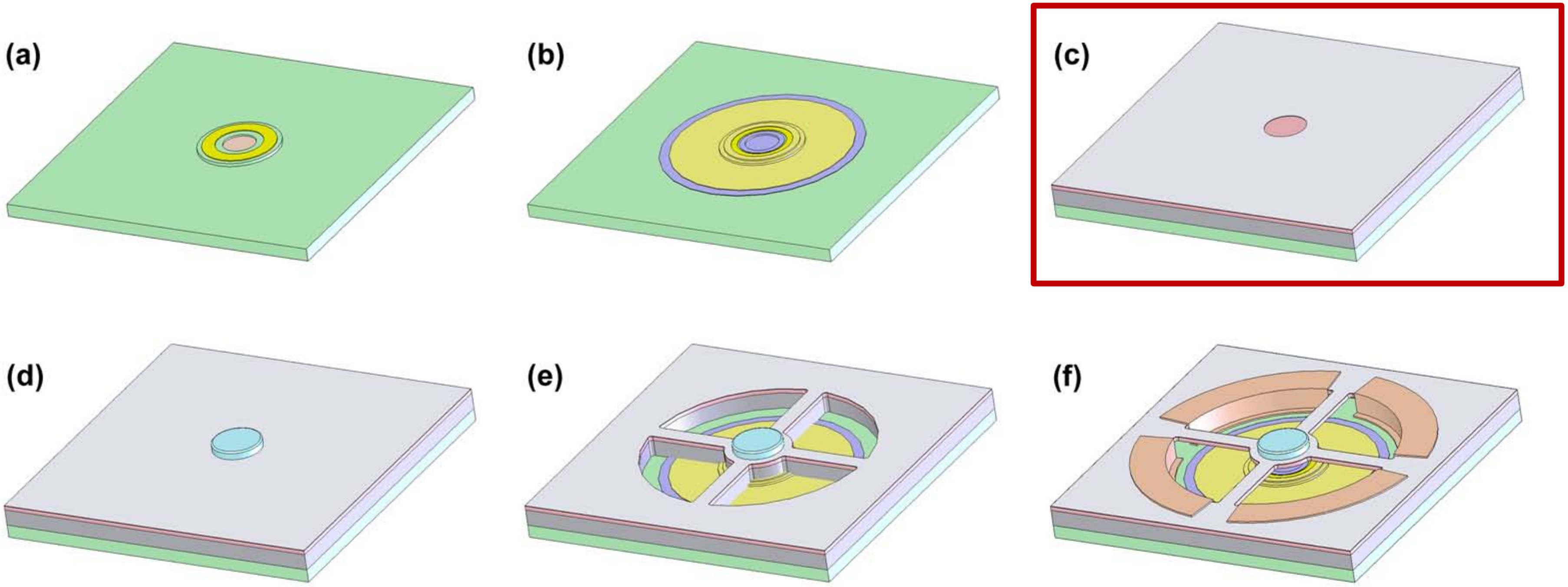

c) α-Ge evaporation, Si_xN_y PECVD, aluminum evaporation and window etch

G. D. Cole, et al., “Fabrication of suspended dielectric mirror structures via xenon difluoride etching of an amorphous germanium sacrificial layer,” *Journal of Vacuum Science and Technology B*, vol. 26, no. 2, March/April 2008, pp. 593–597.

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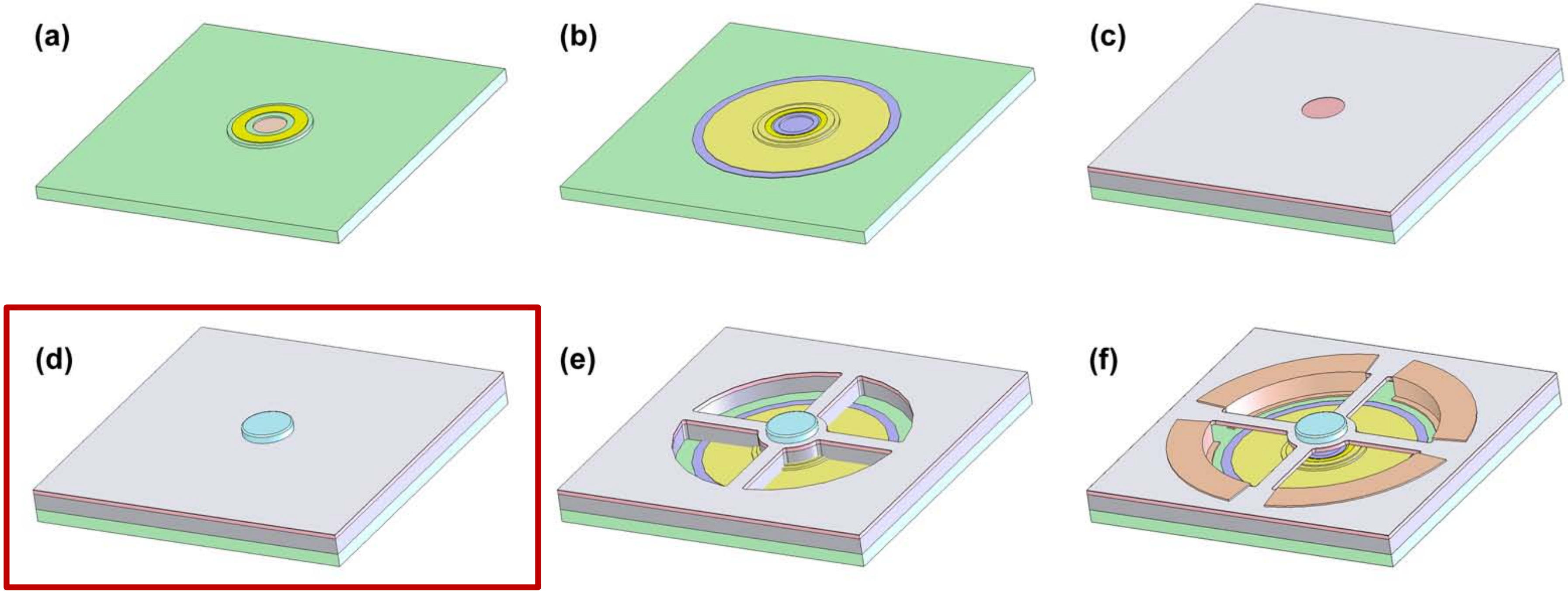

d) evaporation of SiO_2 / TiO_2 DBR; etch back in SF_6 / Ar to aluminum etch stop

G. D. Cole, et al., “Fabrication of suspended dielectric mirror structures via xenon difluoride etching of an amorphous germanium sacrificial layer,” *Journal of Vacuum Science and Technology B*, vol. 26, no. 2, March/April 2008, pp. 593–597.

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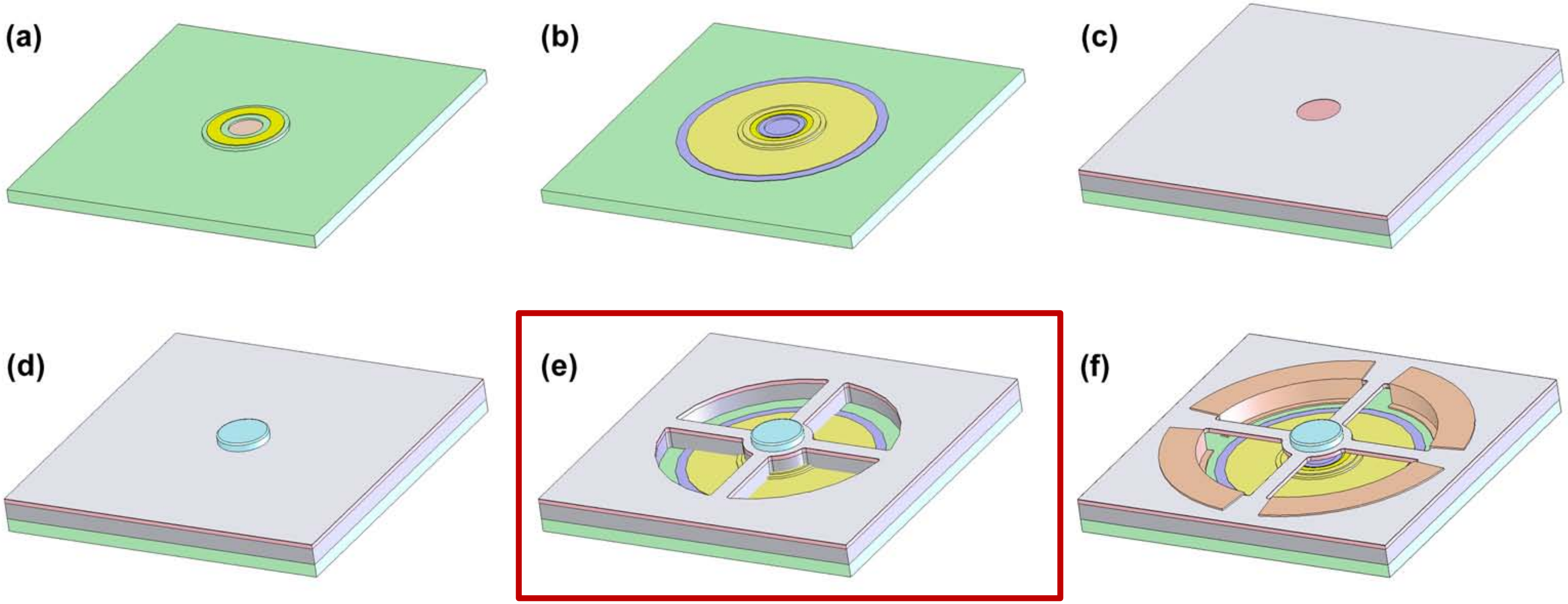

e) Al wet etch followed by ECR etching of actuator geometry with CF_4 / O_2

G. D. Cole, et al., "Fabrication of suspended dielectric mirror structures via xenon difluoride etching of an amorphous germanium sacrificial layer," *Journal of Vacuum Science and Technology B*, vol. 26, no. 2, March/April 2008, pp. 593–597.

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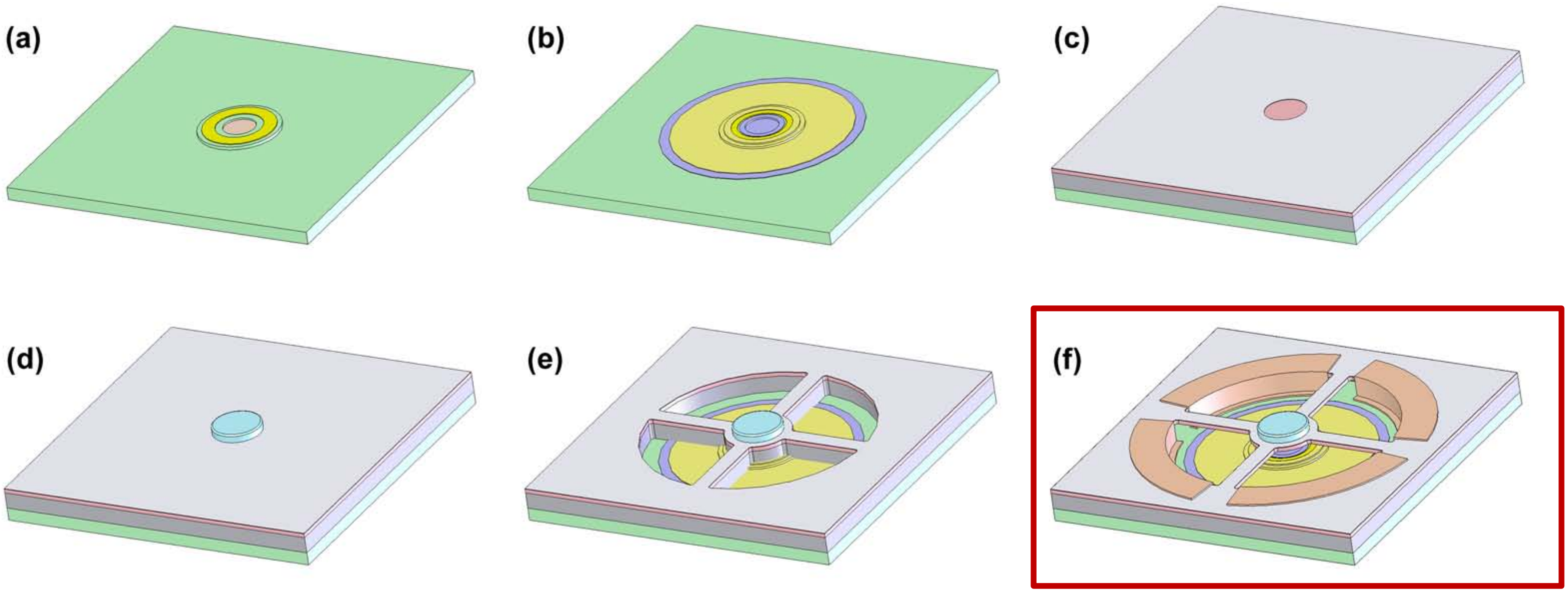


f) undercut protection via liftoff of PECVD SiO_2; process completed with release in XeF_2

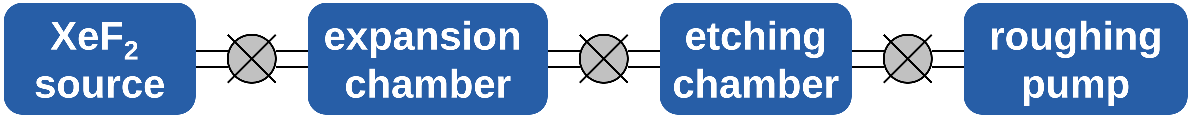
G. D. Cole, et al., “Fabrication of suspended dielectric mirror structures via xenon difluoride etching of an amorphous germanium sacrificial layer,” *Journal of Vacuum Science and Technology B*, vol. 26, no. 2, March/April 2008, pp. 593–597.

Sacrificial Germanium Film

- Low temp. deposition (CVD, PECVD, evaporation)
- Smooth amorphous films realized by evaporation
  - Typical surface roughness values < 10 Å
- Robust compared with polymer sacrificial materials
  - Superior temperature stability
  - Excellent adhesion to III-Vs
- Can be selectively etched via H_2O_2 and XeF_2

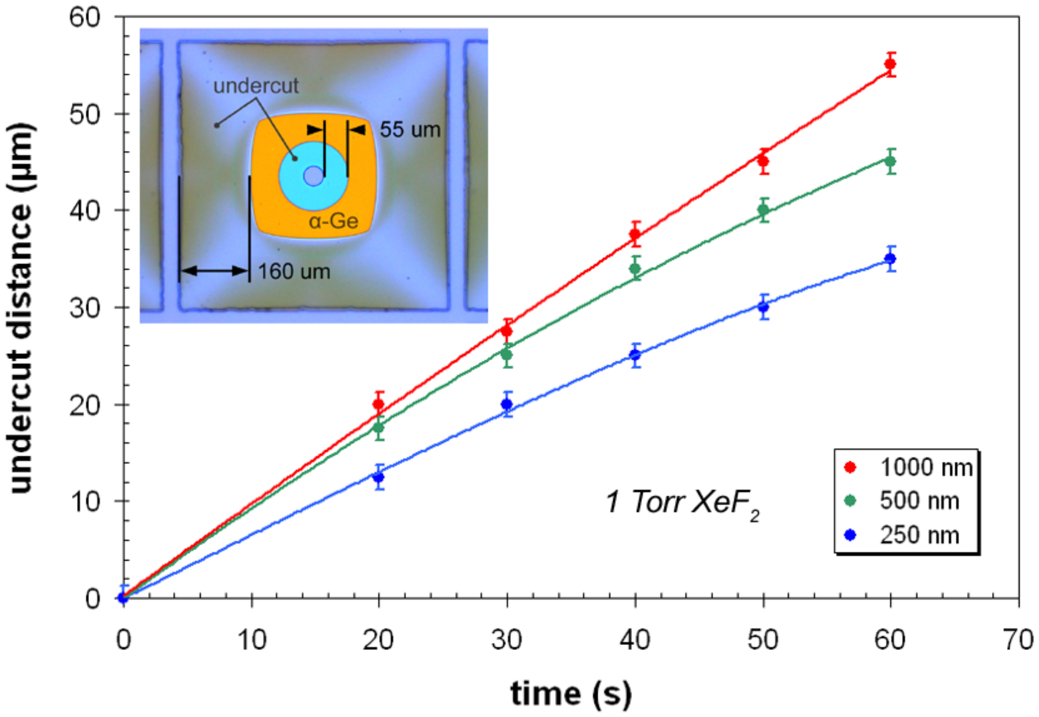
Germanium Etching with XeF_2

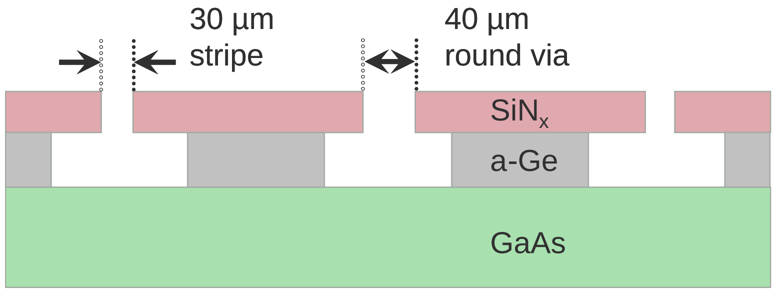
- Developed for gas-phase isotropic silicon etching
- Removes need for CPD
- No plasma damage
- Highly selective to metals, dielectrics, etc.
- Can be viewed in real time (w/ transparent DBR)
- Process yet to be applied to sacrificial germanium



P. B. Chu, J. T. Chen, R. Yeh, G. Lin, J. C. P. Huang, B. A. Warneke, and S. J. Pister, "Controlled pulse etching with xenon difluoride," *Digest of Technical papers Transducers 1997*, Chicago, IL, USA, paper 2D3.01, pp. 665–668.

Sacrificial α-Ge etching with XeF_2

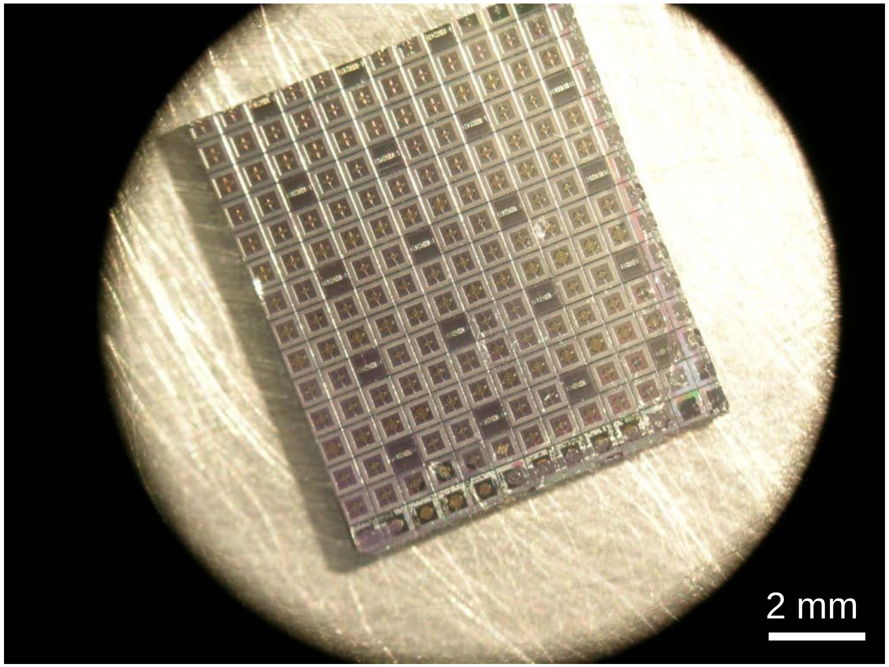


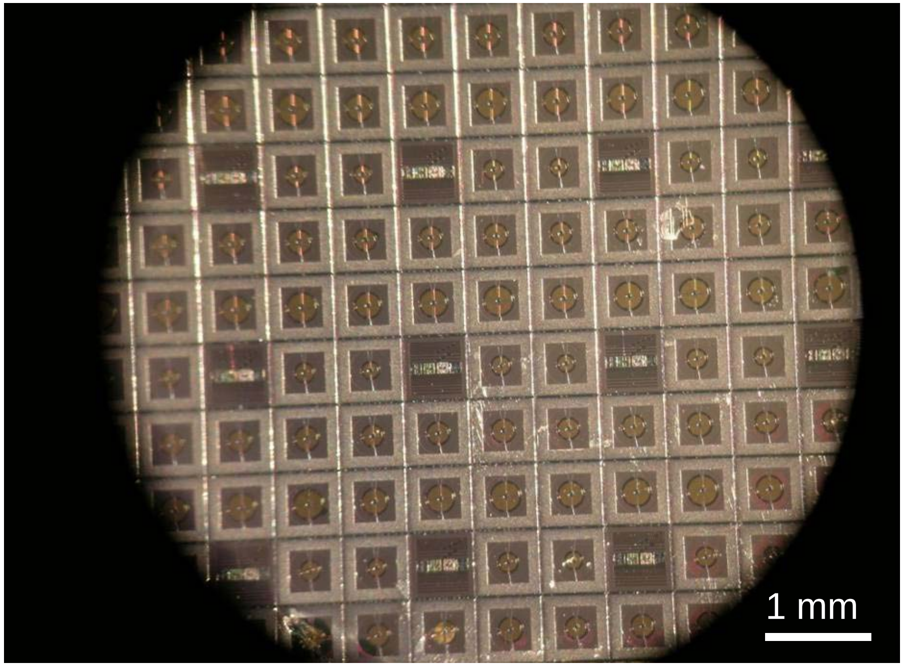


- Maximum achievable silicon etch rate is 10 µm/min (>3 Torr, RT)
- Reaction rate for germanium far exceeds that of silicon
  - at 1 Torr and room temperature, etch rate exceeds 150 µm/min!

G. D. Cole, E. Behymer, “Rapid sacrificial germanium etching using xenon difluoride,” *Hilton Head 2008: Solid-State Sensors, Actuators, and Microsystems Workshop*, 1–5 June 2008, Hilton Head Island, SC. Late News Submission

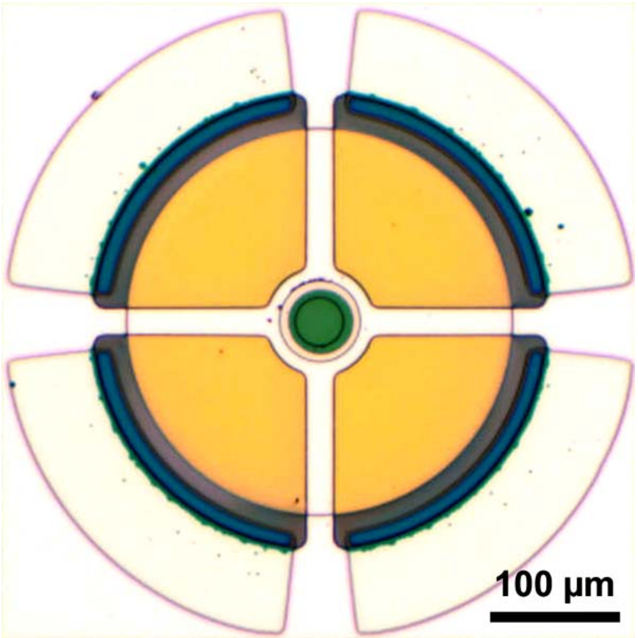
Completed Devices

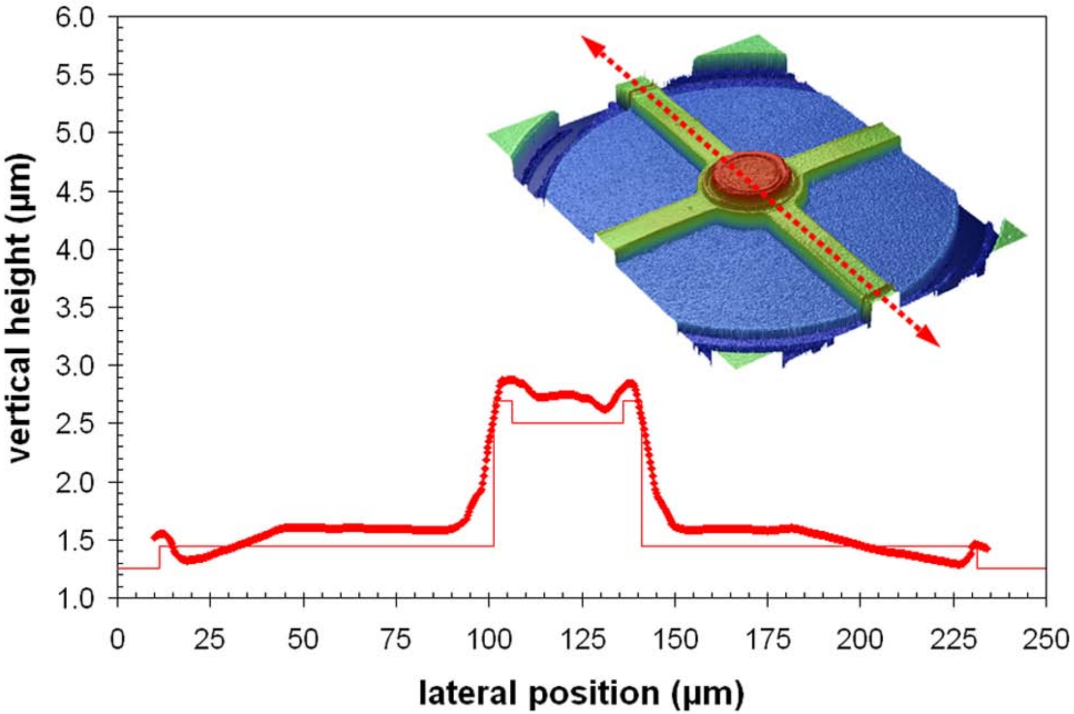




- Samples processed on cleaved 1 x 1 in. squares (3 in. epi wafers)
  - Prior to release the chips are cleaved into 4 sections
- Center to center device spacing of 650 µm
- Laser dicing or post dice release required for die singulation

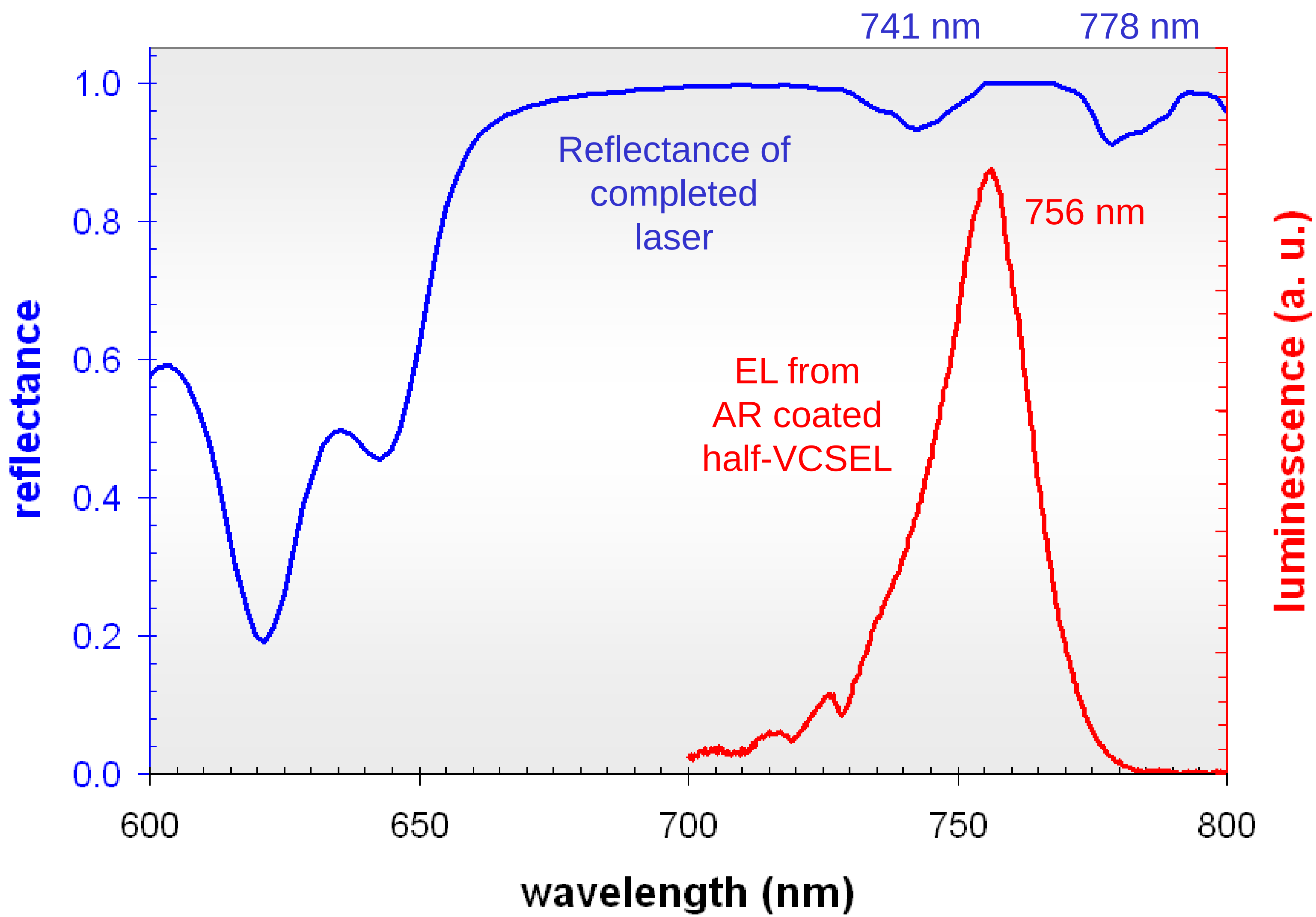
Completed Devices



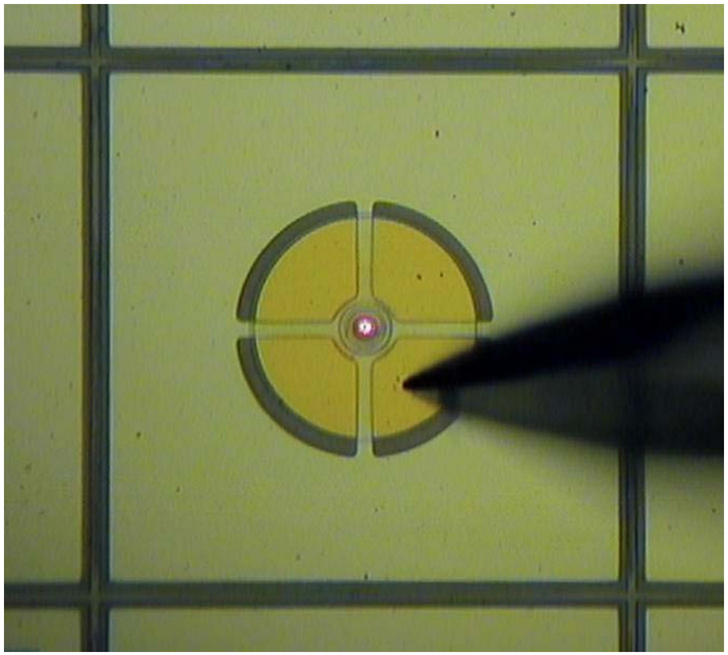


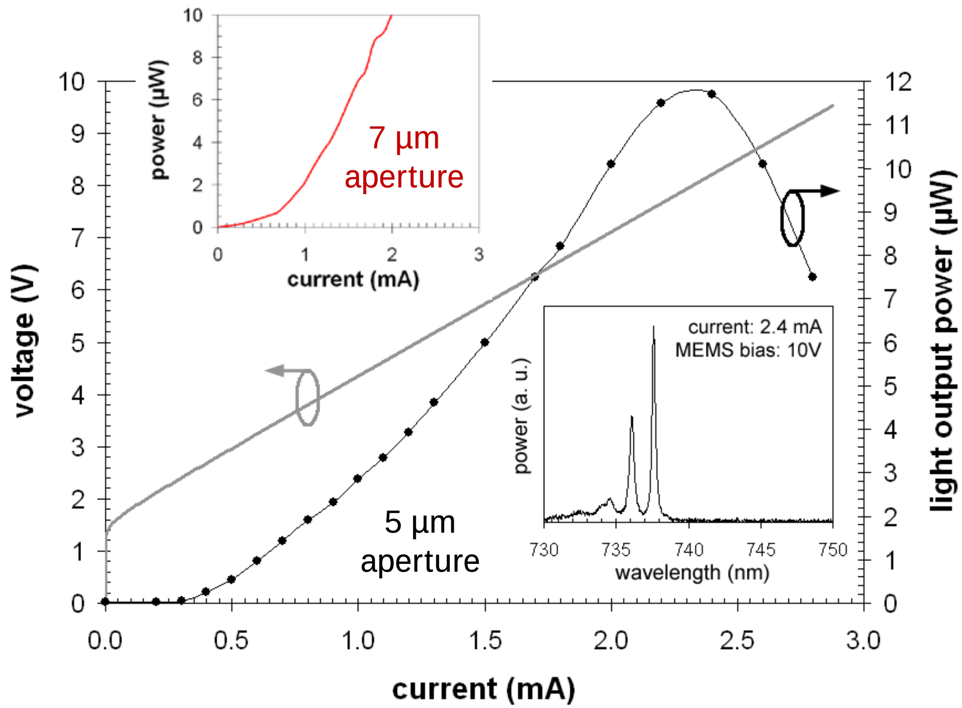
- Optical micrograph of single laser without wire bond pads
- Optical profilometer reveals very slight upward bowing
    - Total initial deflection of ~100 nm, easily compensated via actuation
    - Bimorph effect due to CTE mismatch of aluminum and silicon nitride

Reflectance and Luminescence



L-I-V Characterization

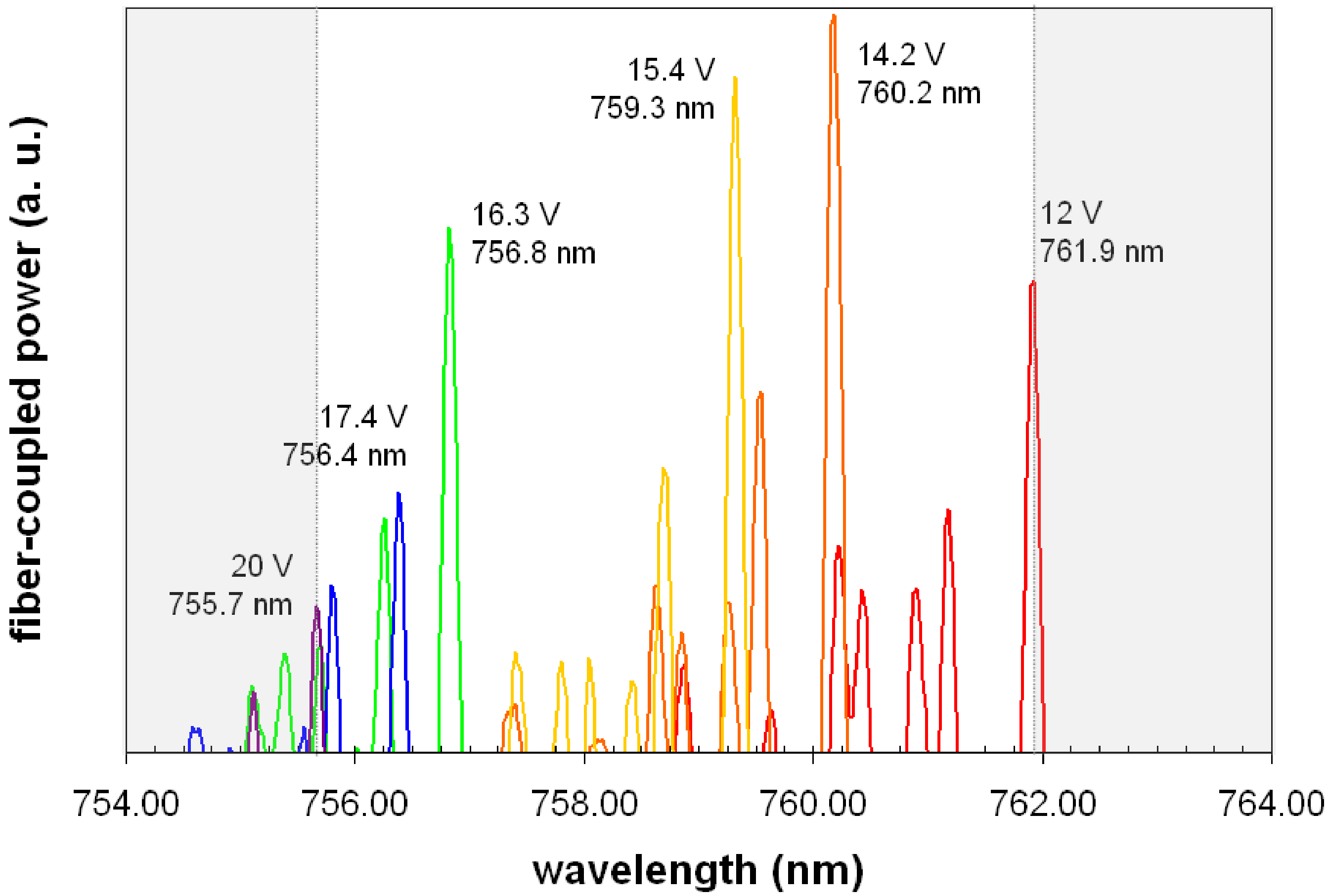




- Emission is properly confined to aperture (deep red color to eye)
- Devices are highly resistive: ~3 kΩ, bias reaches 10 V by 3 mA
  - threshold of 0.4-0.8 mA (1.6 kA/cm^2) and output powers of 10-20 µW
  - device lifetimes are extremely poor, less than 1 hour CW

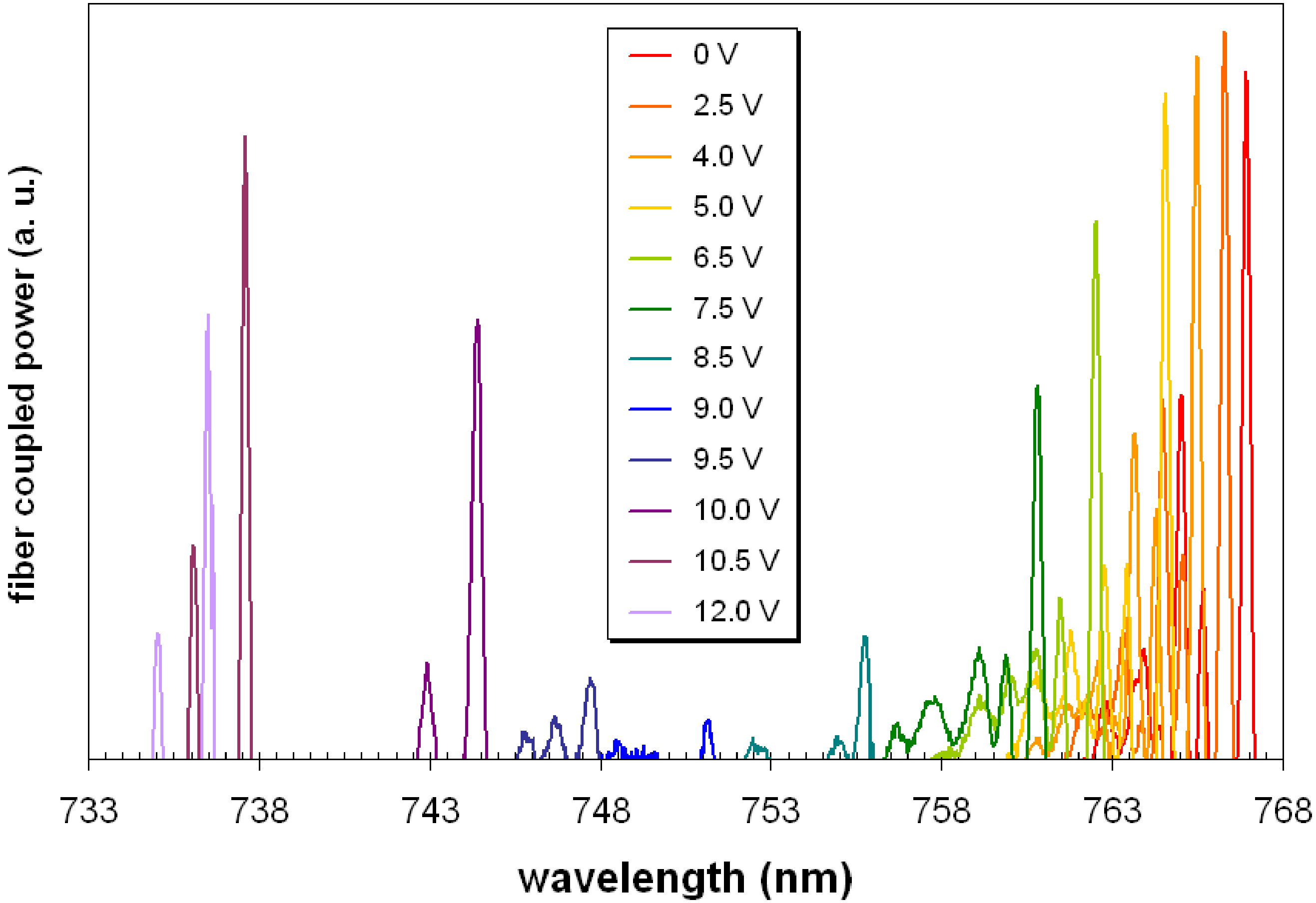
Multimode Tuning Response

- Continuous tuning over 6.2 nm (12-20 V on actuator)



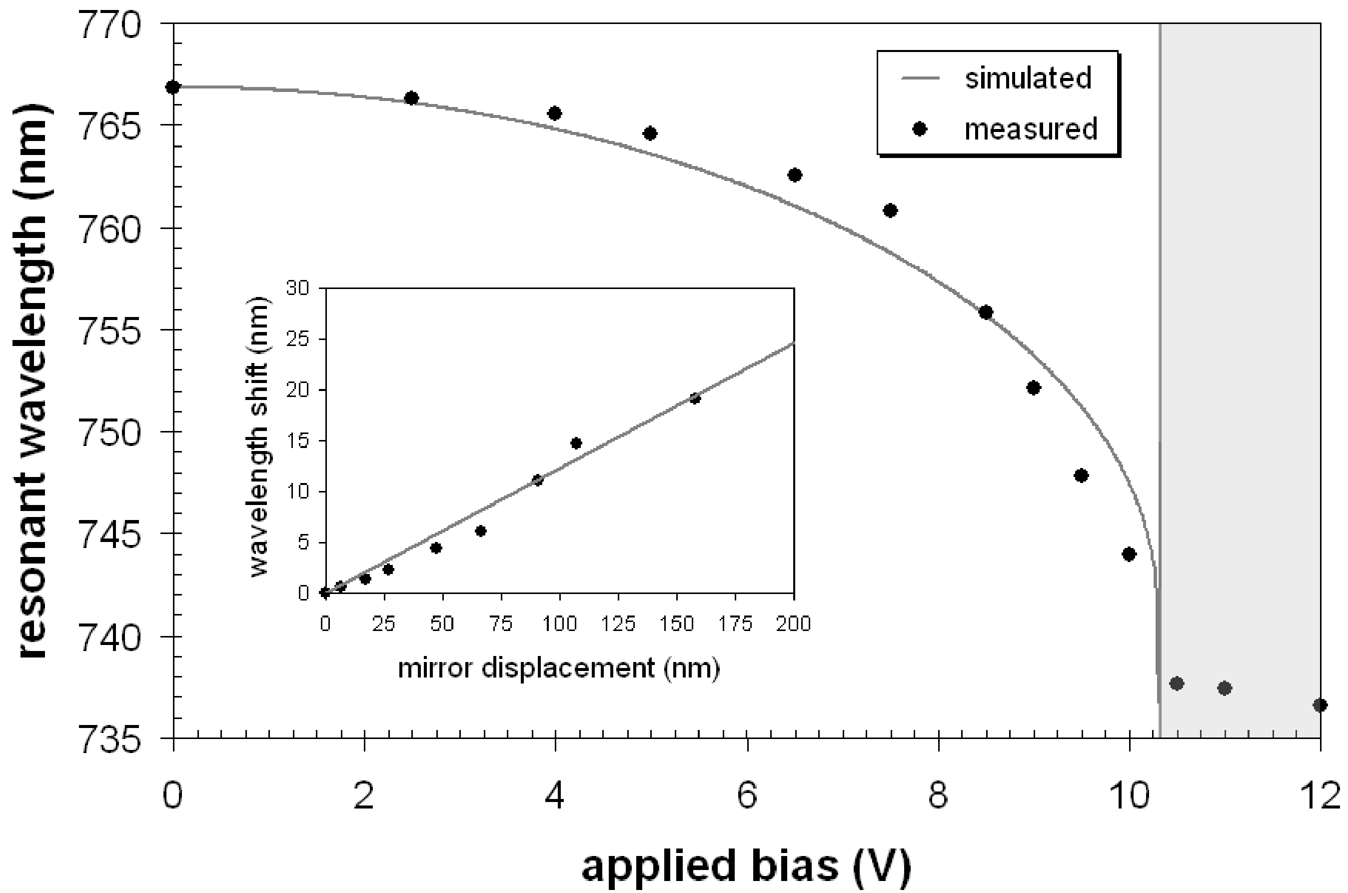
Widest Tuning Measured

- Discontinuous tuning over 30 nm (ideal initial air gap)



Extended-Cavity Tuning Response

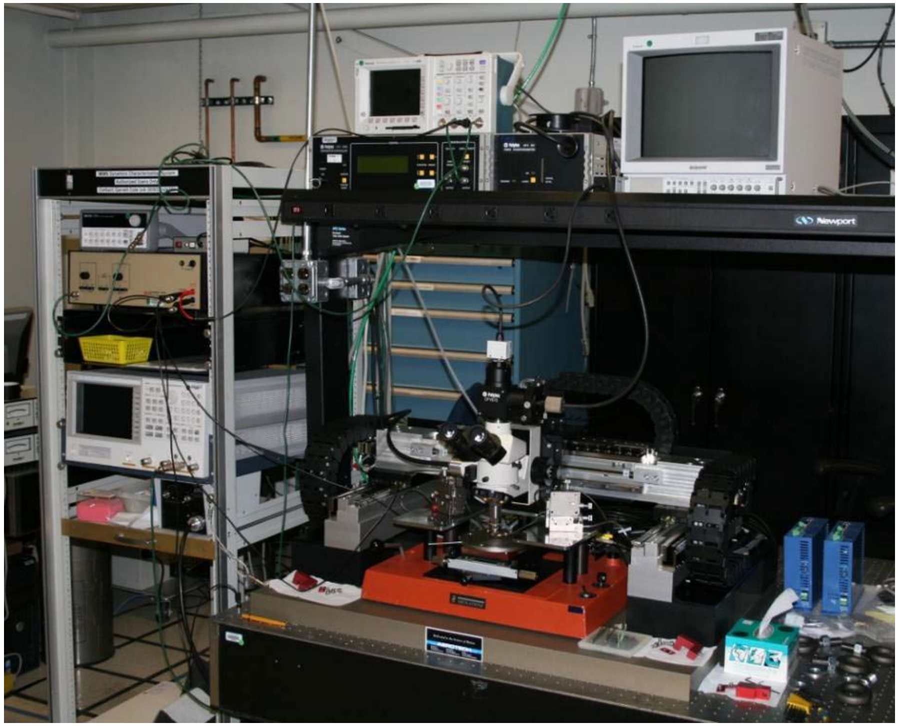
- Linear resonance tuning as a function of displacement

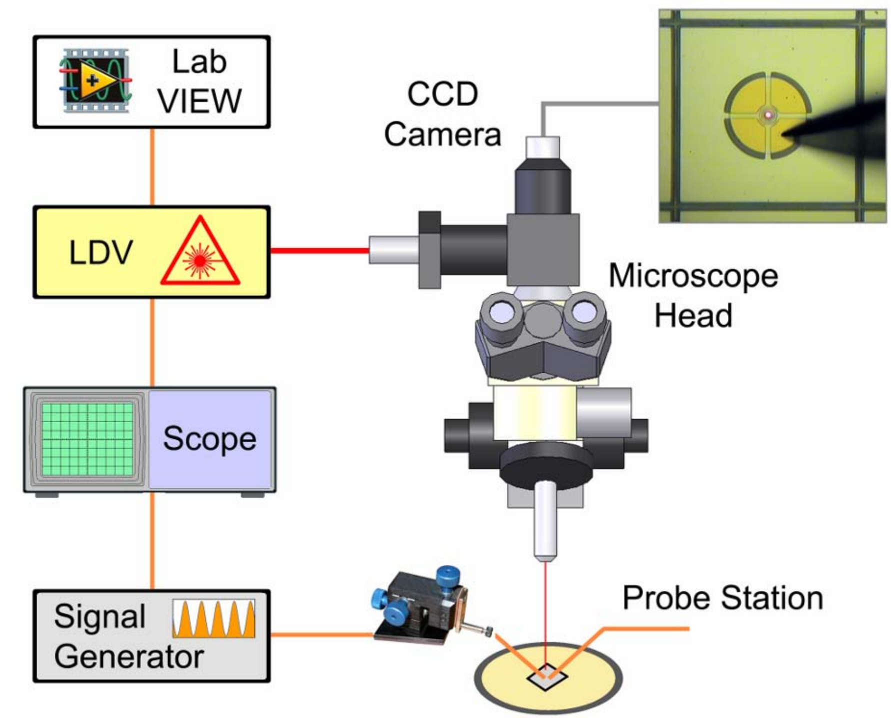


Initial Design Deficiencies

- Excessive resistance due to thin current spreader
  - 285-nm thick p-type $Al_{0.30}Ga_{0.70}As$ (carbon at 2×10^{18} cm^{-3})
  - TLM patterns on chip yield 10^{-6} $\Omega\cdot cm^2$ contact resistance
  - Large aperture devices show reasonable voltages
- Extremely poor device lifetime in CW operation
- Excessive reflectivity of MEMS-tunable DBR structure
  - Poor repeatability in dielectric DBR deposition
  - Excess periods to ensure lasing (may exceed epi DBR reflectance)
- Discontinuity in tuning: oxide modes?
  - Lower threshold calculated under oxide aperture over relevant λ

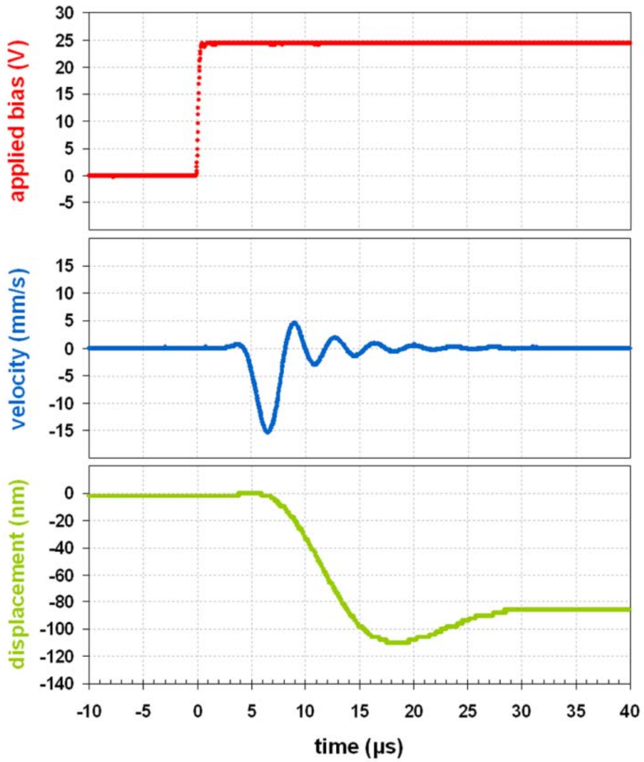
MEMS Motion Characterization

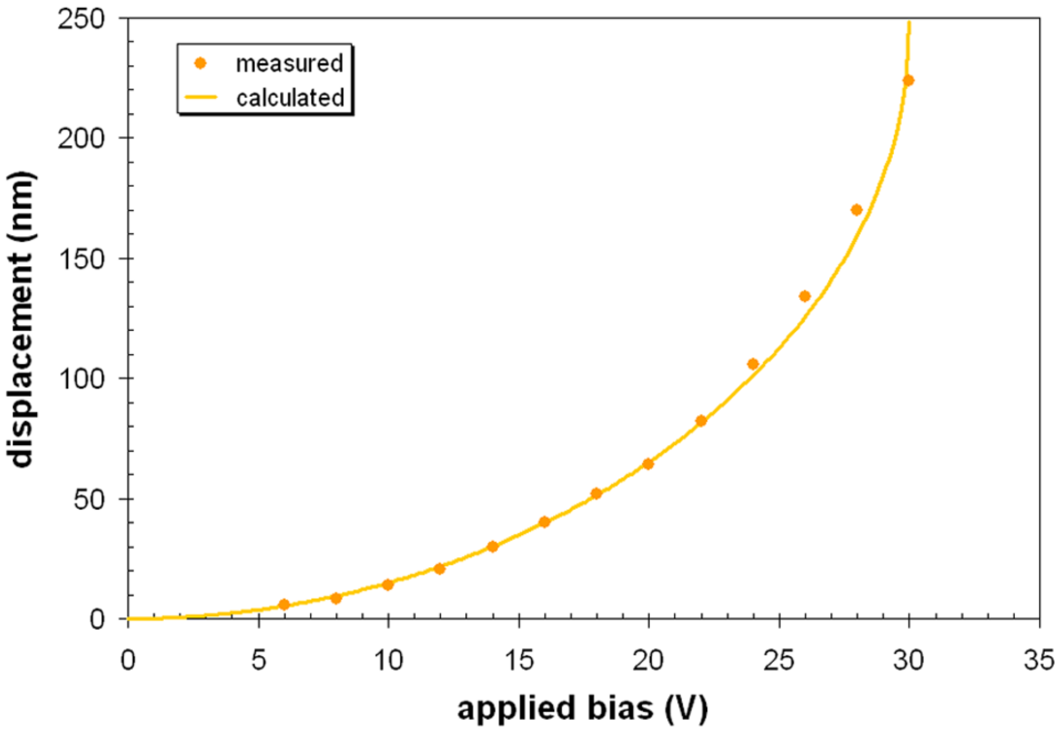




- Microscope-coupled laser Doppler vibromer (LDV)
- Non-contact time and frequency domain characterization
  - Temporal measurements and frequency response to 1.5 MHz (velocity)
  - Sub-nanometer displacement resolution

Quasi-Static Displacement Response

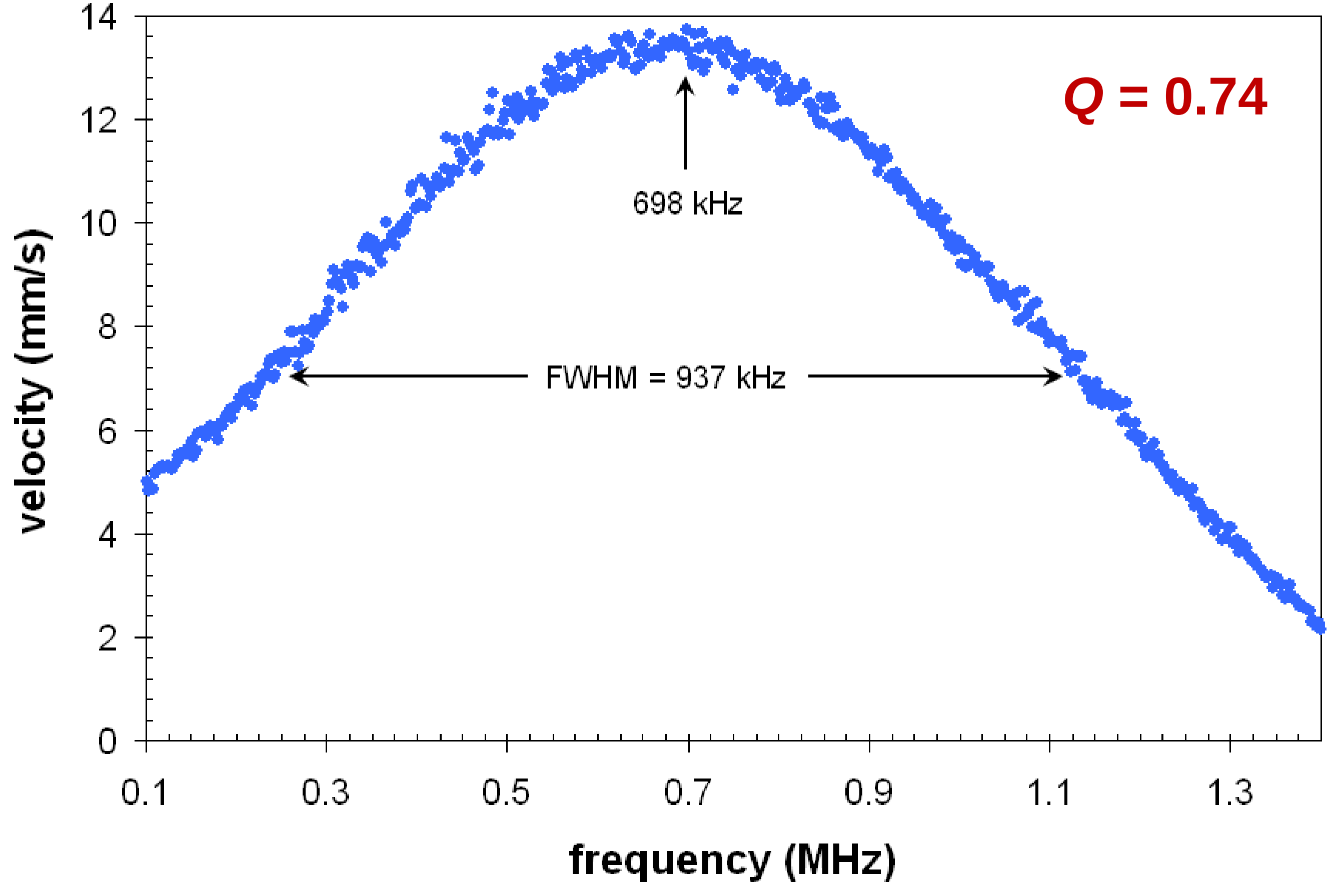




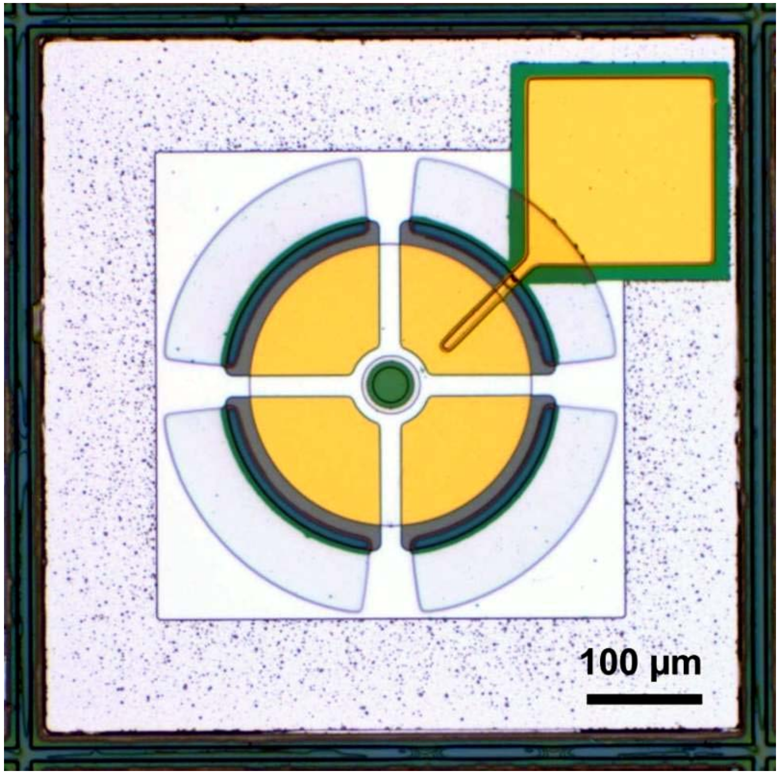
- Generation of displacement vs. bias from step response
- For all devices maximum displacement reached by < 30 V
    - Note the significant non-linearity in the electrostatic actuator
    - Transient response is not physical due to limited bandwidth of LDV

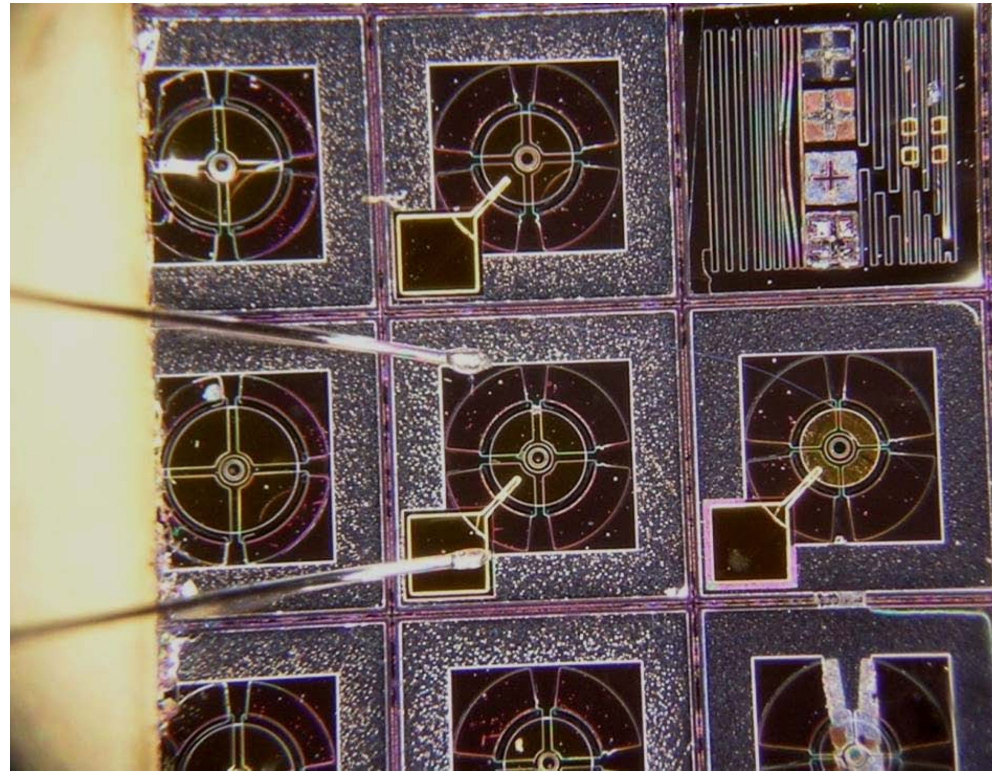
Typical Frequency Response

- Resonance up to 1 MHz, significant squeeze film effects



Initial Packaging Trials





- Wire bonding process successfully developed on completed chips
  - Al wire used to contact laser drive and MEMS actuation pads
- Die singulation must involved “MEMS friendly” processes
  - Laser dicing or XeF_2 undercut following standard dicing process

Future Directions

- Improved epi design to reduce diode resistance
  - Alter current spreading layer and position of oxide aperture
  - Investigate alternative DBR doping strategies
- More detailed analysis of laser properties
  - Demonstration of O_2 sensing
- Optimize packaging procedure for singulated die
- Confocal cavity geometry for improved performance

Summary

- Demonstration of MEMS-tunable VCSELs with $730 < \lambda < 770$ nm
  - Current-injected EC-design AlGaAs half-cavity with oxide aperture
  - Electrostatic actuation of suspended dielectric DBR structure
  - Development of a novel gas-phase sacrificial Ge release process
- Multimode operation with discontinuous tuning over 30 nm
  - Potential for continuous tuning over ~5% of emission wavelength
  - MEMS bandwidth exceeding 1 MHz: sub-µs tuning possible

- Acknowledgements
  - E. Behymer: fab support; L. Goddard: test setup; T. Bond: project management
  - B. Kögel, J. Geske, and M. MacDougal for numerous insightful discussions