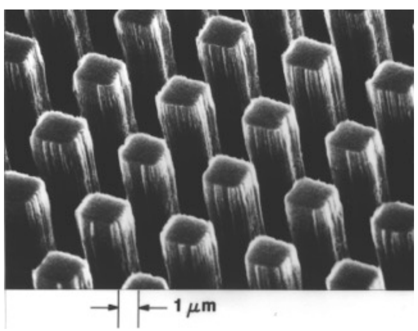
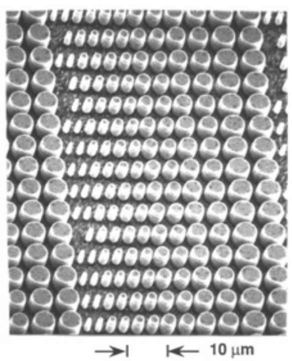
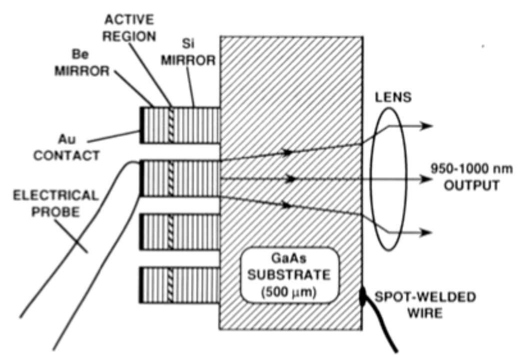
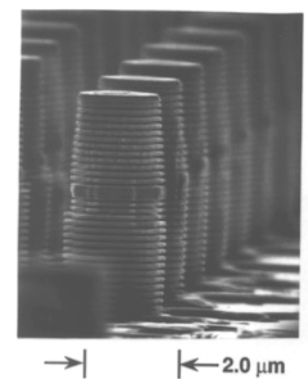
A 1989 Event in VCSEL Development

Jack Jewell









1st Visit to Japan – July 1969

EXTRA No. 1

The Japan Times

'All the News Without Fear or Favor'

© The Japan Times 1969 MONDAY, JULY 21, 1969

APOLLO LANDS ON MOON

Astronauts Describe Rocky Lunar Terrain

SPACE CENTER, Houston (AP)—Man landed on the moon at 4:18 p.m. EDT, Sunday, July 20 (5:18 a.m. JST, Monday).

Two men, Neil A. Armstrong and Edwin E. Aldrin Jr., 240,000 miles away from their home planet called earth and their nation, the United States of America, came to a dusty landing on the moon's surface, the first men to touch its alien soil.

"Tranquillity base here," said Armstrong. "Eagle has landed."

"Beautiful beautiful," rang out over world television networks.

Astronaut Wally Schirra was virtually speechless, with tears in his eyes. Schirra served as commentator for a television network.

There were no complaints about the landing craft's position, just some little dust.

"They have landed at Tranquillity Base," Houston space center announced to a waiting world. Thousands of people gathered in midtown Manhattan streets to see the TV show reproduced outdoors.

From some 60-odd miles (90 km.) above the moon, Michael Collins in the command ship Columbia chimed in with "Fantastic."

The unofficial time of the Eagle's landfall on the moon's Sea of Tranquillity was 102 hours, 45 minutes and 42 seconds after blastoff last Wednesday, July 16, from Cape Kennedy.

The first minutes on the lunar surface were mostly silent, as Armstrong and Aldrin quickly readied everything in their spider-like space taxi for an emergency blast-off from the moon, if necessary.

The initial moments were for a decision on whether to stay on the dusty surface. The spacecraft engine began kicking up dust from the moment it was 40 feet (12 meters) above on its descent.

The two landed astronauts passed up their time for a first liftoff should they have needed to make one.

As they rested for the actual stepping on to the moon, earth listeners were told it would be some time before they would get a man's eye view of the landing.

Commander Neil Armstrong took over manual control for the landing, the space center was informed.

One of the astronauts reported he "wanted a beer." He was promised that by the space center who cheered "a great job by you guys" in the conversation with the Sea of Tranquillity landers.

Armstrong's first description of the landing area was terse. He apologized for taking a little longer than planned in his landing.

"The auto-targeting was taking us right into a football field-sized crater," he said, "with a large number of big boulders and rocks—and it required us to fly manually over the rock field to find a reasonably good area."

Aldrin looking out the window said, "Almost every variety of rock you could find. The color

He said the rocks were "of every granularity, every angularity."

The three lunar astronauts who did little chatting on their voyage suddenly became very communicative after the landing—tossing patter back to earth.

In the command module Astronaut Collins had a man's eye view of the landing and received a stream of congratulations from the space center that "You're looking good."

Space authorities predicted that the easy landing should have preserved the astronauts' television cameras perfectly for good transmission later, including the first moon steps.

During the descent, Armstrong said, he was too busy with the control panels to pick out some of the required landmarks. Mission control told him not to worry.

Commander Armstrong told earth: "No difficulty so far adjusting to the gravity of the moon."

The astronauts described angular blocks on the moon's rugged surface. "It was extremely rough and cratered over the landing target area," they repeated.

U.S. President Richard Nixon watched the televised news of the landing in his working office in the executive office building next door to the White House.

It was different view for the astronauts on the moon.

"We are in a relatively smooth plain with many craters 5 to 50 feet in size," Armstrong reported. "We see some ridges. And there are literally thousands of little one and two foot craters. We see some angular blocks some feet in front of us, about two-to-three feet in size.

"There's a hill in view on the ground track ahead of us. It's difficult to estimate but it might be one-half mile or a mile away." The normal lunar horizon is 1½ miles away."

Of the rocks on the moon, Armstrong said: "Many of them were larger than 10 feet."

The two Americans began the dangerous descent to the moon's surface from lunar orbit at 4:09 a.m. JST Monday, an hour away from man's first landing on a foreign planet.

"The Eagle has wings," Neil Armstrong told the world as his lunar lander took life and carried him toward that magic moment when he would take man's first steps on the moon.

The Eagle came around the backside of the moon for the 14th time, with Armstrong and Aldrin at the controls.

"Everything is going along just swimmingly," said Michael Collins aboard the command ship Columbia, high above the descending Eagle.

There was some momentary communications difficulty as Eagle lost antenna tracking with ground stations. During that time, mission control passed on messages to Eagle through Columbia.

The two Americans who will walk the moon cast off from their mother ship at 2:47 a.m. JST Monday.

Coming from their radio blackout behind the moon for the 13th time, the Apollo 11 astronauts confirmed the maneuver was perfect.

Air Force Lt. Col. Michael Collins in the command ship pressed a button, latches released and powerful springs shoved eagle away from the mother ship, Columbia.

Twenty-five minutes later, with the two ships 40-feet apart, Collins triggered his big spacecraft rocket and shot nearly two miles ahead of the spidery moon lander.

All systems checked out well and gave the Eagle the go-head to begin their descent into a lower orbit. When the lander reached 50,000 feet (15,240 meters) an hour later, the engine fired again to gently lower the craft to the moon.

Within ten hours after landing (at 3:16 p.m. JST Monday), Armstrong and Aldrin would walk the moon, fulfilling an American pledge to put a man on the moon in this decade.

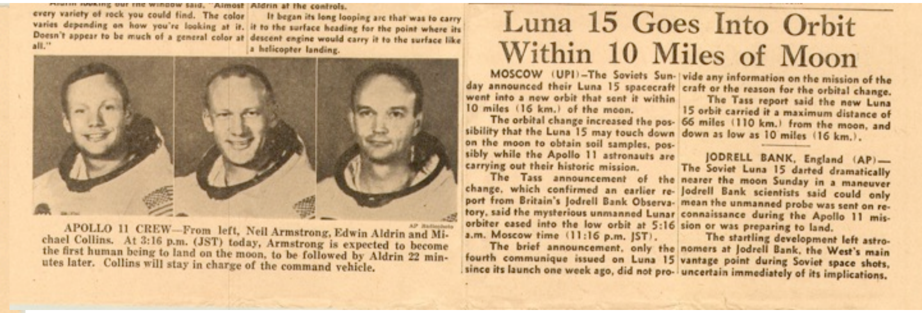
Meanwhile Collins would keep his lonely vigil in Columbia, the command ship, patrolling the moon in an orbit some 60-odd miles above, standing by to take them home.

Aldrin, the pilot of the spidery lunar lander was the first into that strange craft, linked nose to nose with the mothership.

He entered at 10:20 p.m. JST Sunday through the tunnel connecting the two ships. About an hour later, spacecraft commander Armstrong slipped through to join him. From then on Armstrong and Aldrin carried the radio call sign Eagle, Collins became Columbia.

At 1:32 a.m. JST they pushed a button that extended the landing legs of the lunar landing craft, the legs that would take the impact of the landing, an intended four-foot free fall to the surface with the engine shut down.

The astronauts awakened at 7:02 a.m. (2002 JST). They took half an hour for breakfast. Then Armstrong and Aldrin donned the heavy protective suits they would wear when first Armstrong, then Aldrin walk the moon.



every variety of rock you could find. The color varies depending on how you're looking at it. Doesn't appear to be much of a general color at all."

It began its long looping arc that was to carry it to the surface heading for the point where its descent engine would carry it to the surface like a helicopter landing.

APOLLO 11 CREW—From left, Neil Armstrong, Edwin Aldrin and Michael Collins. At 3:16 p.m. (JST) today, Armstrong is expected to become the first human being to land on the moon, to be followed by Aldrin 22 minutes later. Collins will stay in charge of the command vehicle.

Luna 15 Goes Into Orbit Within 10 Miles of Moon

MOSCOW (UPI)—The Soviets Sunday announced their Luna 15 spacecraft went into a new orbit that sent it within 10 miles (16 km.) of the moon.

The orbital change increased the possibility that the Luna 15 may touch down on the moon to obtain soil samples, possibly while the Apollo 11 astronauts are carrying out their historic mission.

The Tass announcement of the change, which confirmed an earlier report from Britain's Jodrell Bank Observatory, said the mysterious unmanned Lunar orbiter eased into the low orbit at 5:16 a.m. Moscow time (11:16 p.m. JST).

The brief announcement, only the fourth communique issued on Luna 15 since its launch one week ago, did not provide any information on the mission of the craft or the reason for the orbital change.

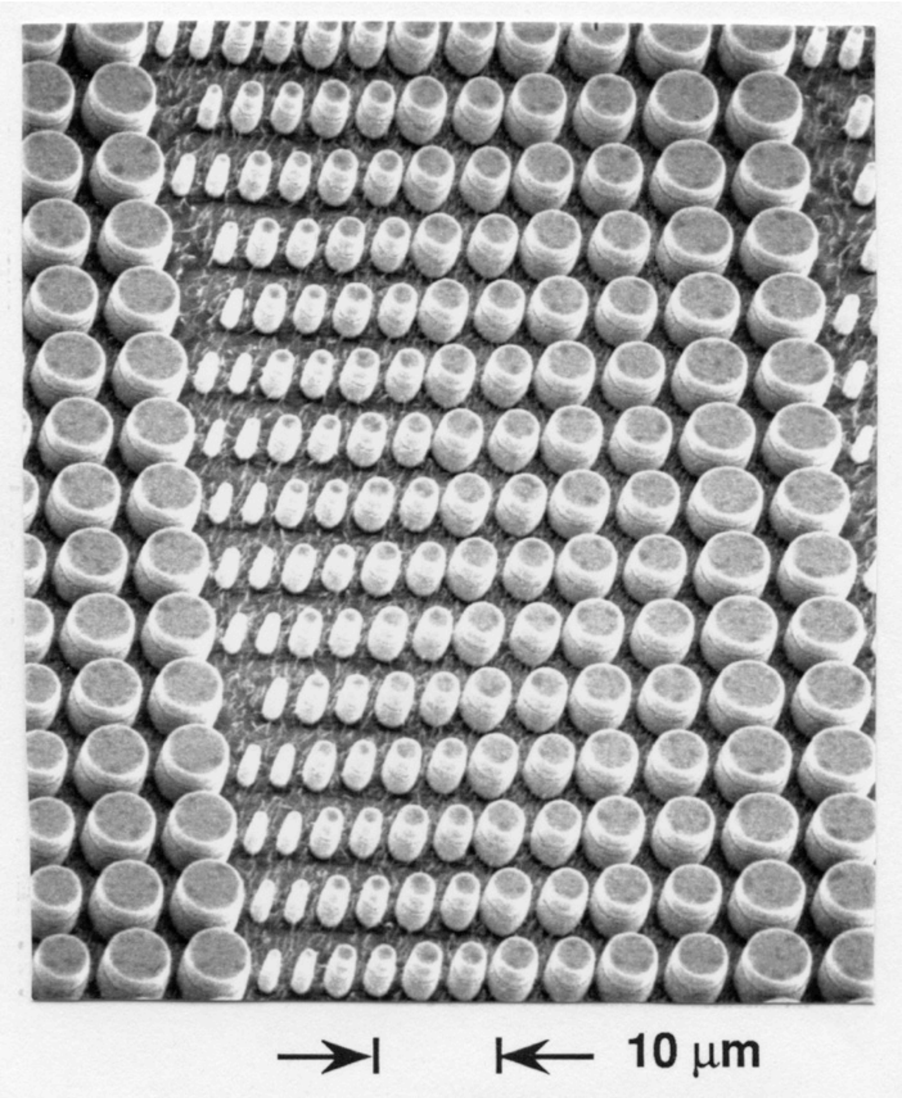
The Tass report said the new Luna 15 orbit carried it a maximum distance of 66 miles (110 km.) from the moon, and down as low as 10 miles (16 km.).

JODRELL BANK, England (AP)—The Soviet Luna 15 darted dramatically nearer the moon Sunday in a maneuver Jodrell Bank scientists said could only mean the unmanned probe was sent on reconnaissance during the Apollo 11 mission or was preparing to land.

The startling development left astronomers at Jodrell Bank, the West's main vantage point during Soviet space shots, uncertain immediately of its implications.

Tokyo Tower

Pivotal Career Event – July 1989



1st announced in Japan

Postdeadline July 1989
IOOC - Kobe?
20 years after Apollo 11

Climbed Mt Fuji w/ John Bowers afterward

VCSEL Anniversaries

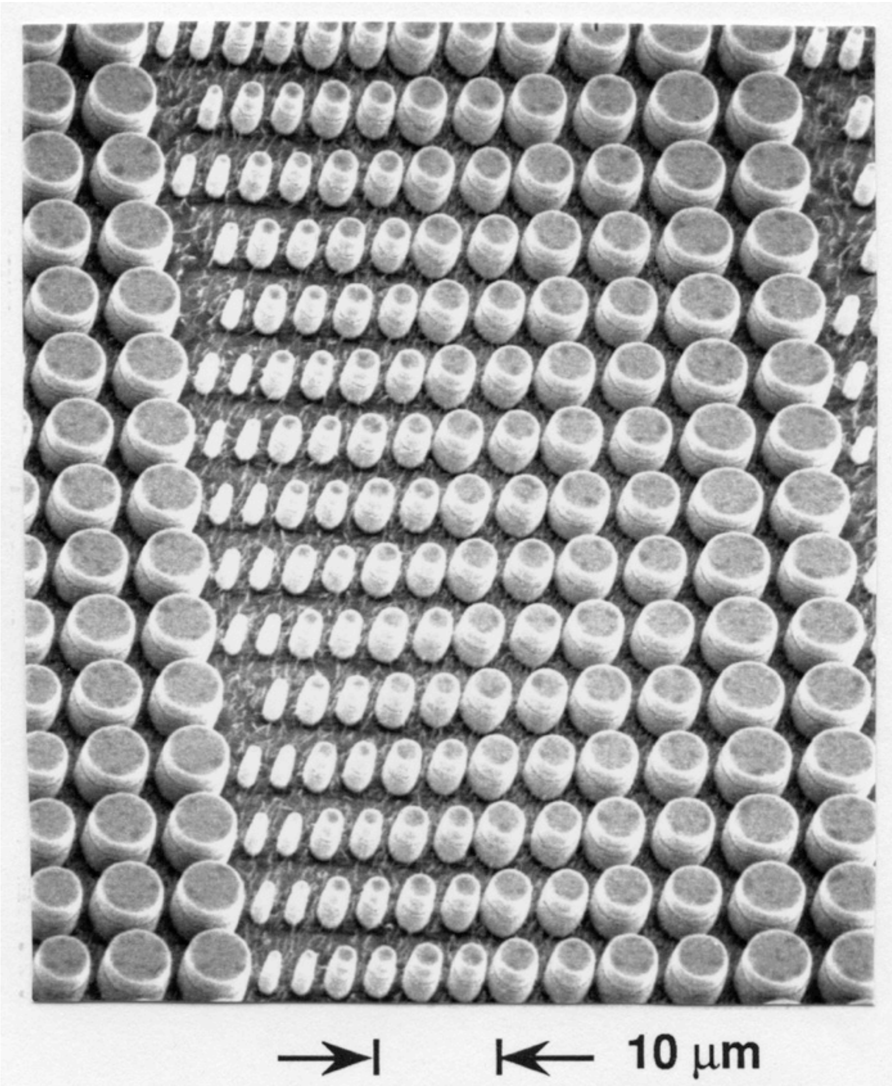
VCSEL originated in Japan

Wonderful celebration/conferences with colleague/friends, hosted by its inventor Kenichi Iga

Run around Mt Fuji – May 2012

Last Friday – Japanese Alps

1st Attempt at a Diode Laser

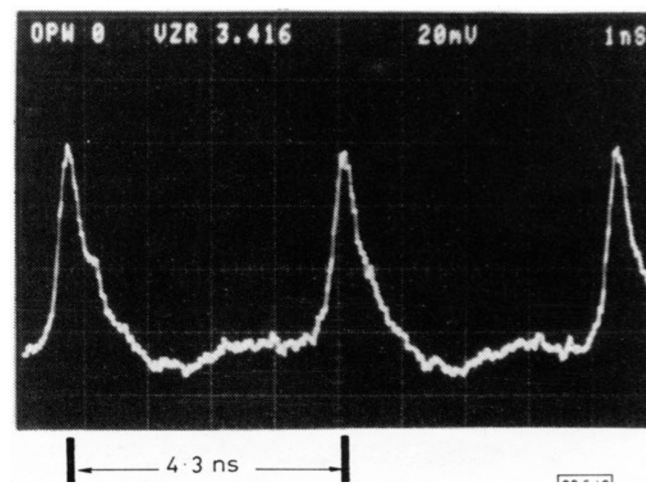


What significance?

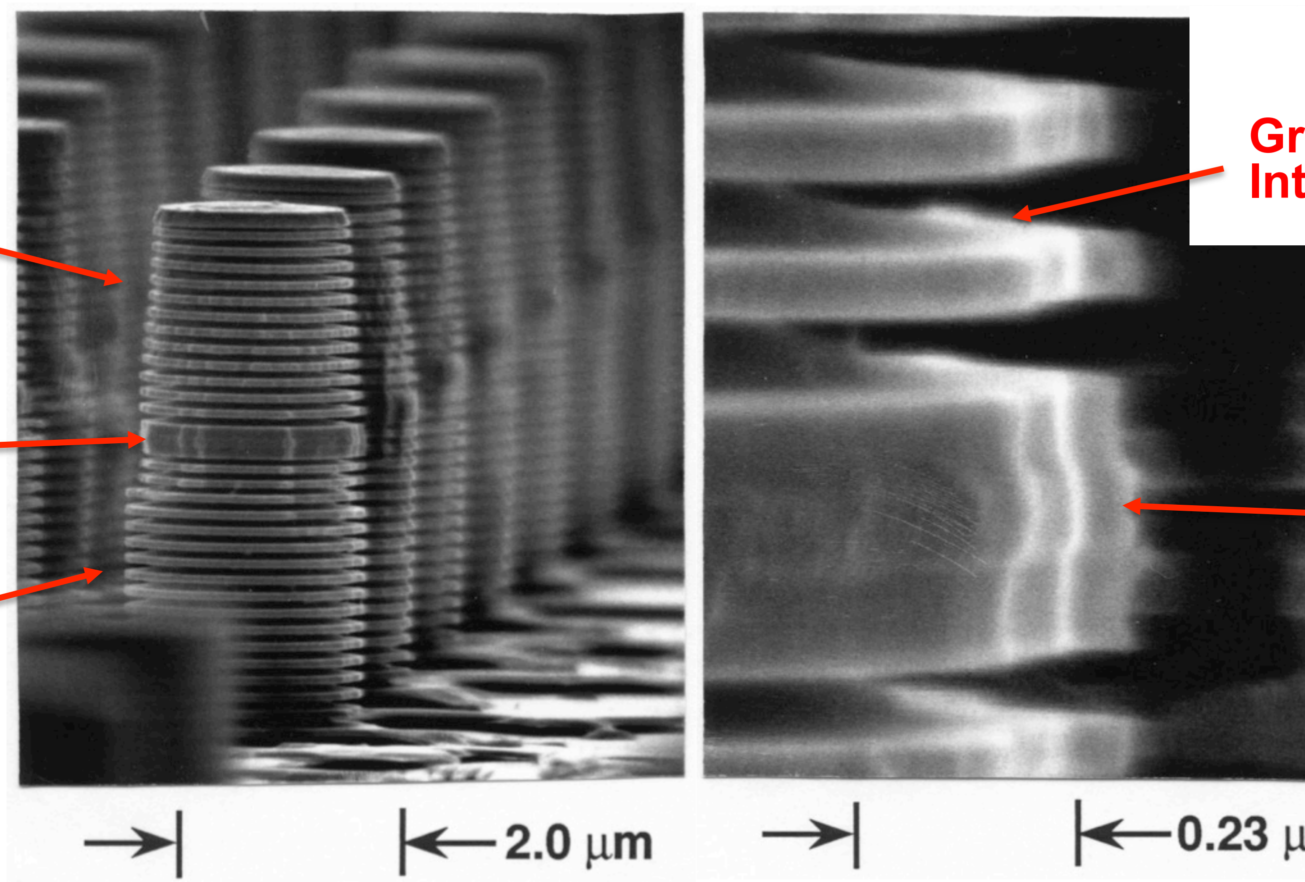
How can this be?

What impact?

nation.[11] The fast carrier recombination and high mirror resistances caused substantial heating preventing room-temperature CW operation. No heat-sinking was used. We did operate with duty cycle as high as 40%. The reduction of

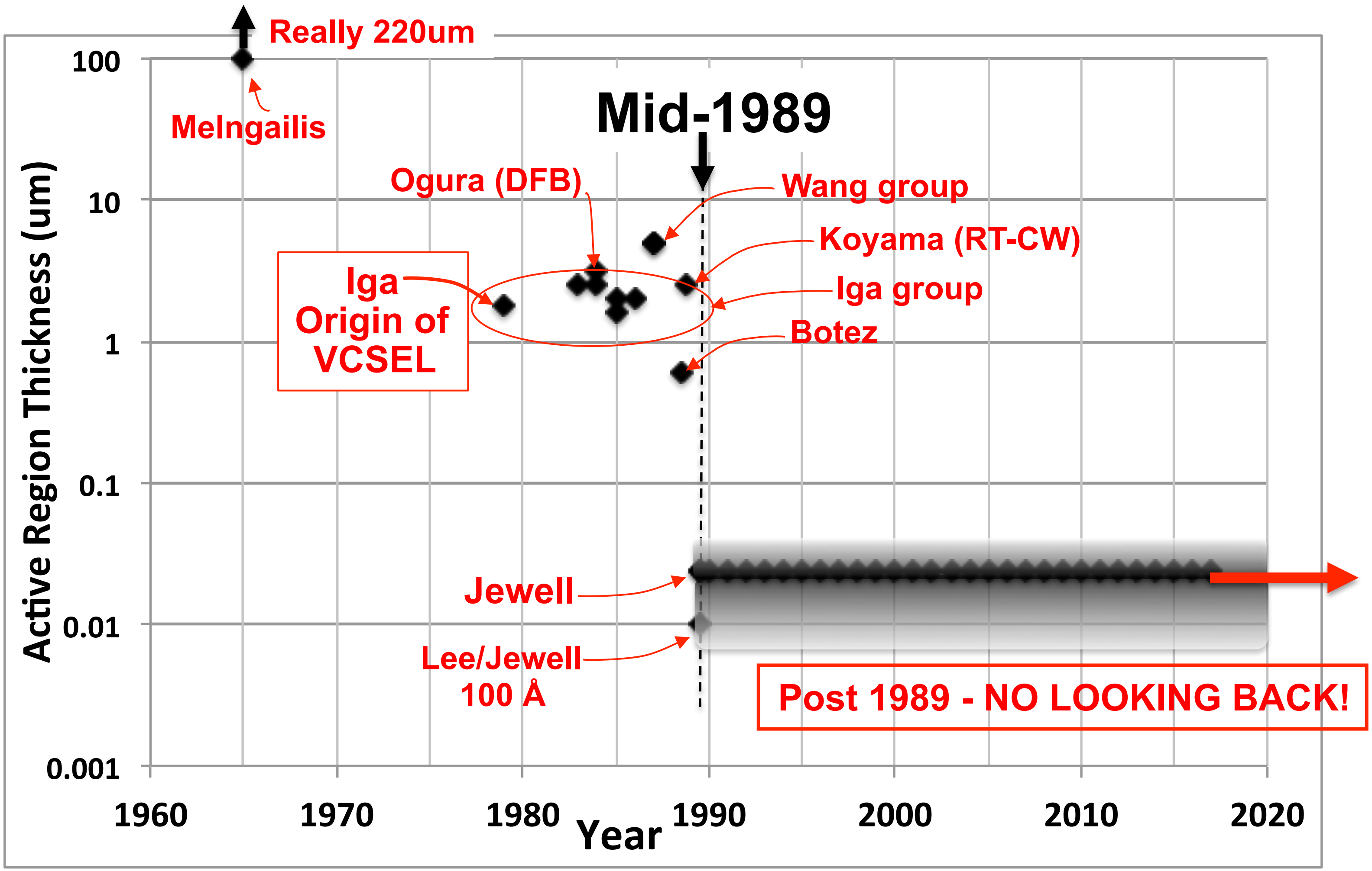


All-Epitaxial Structure, Mostly Mirrors

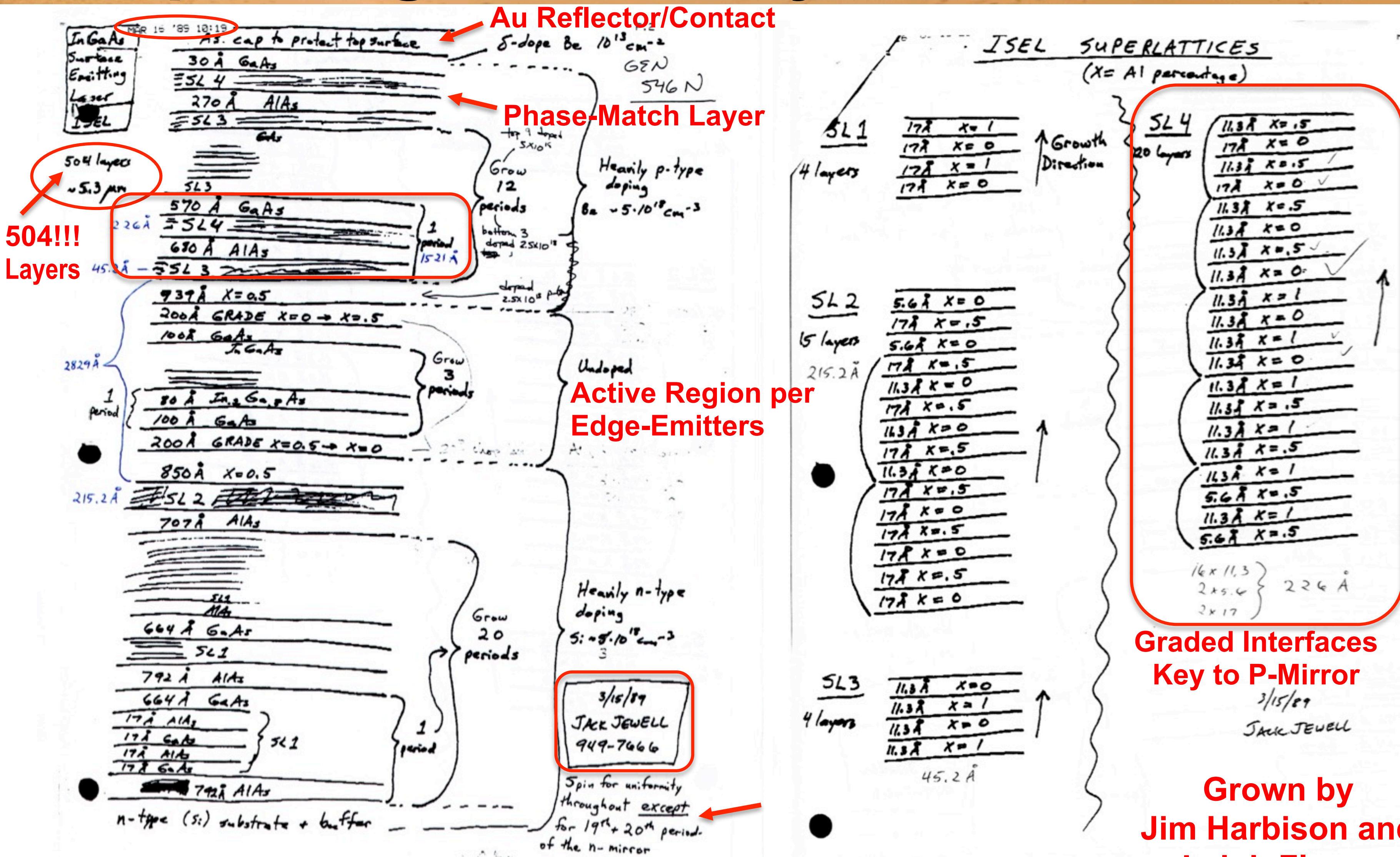


VCSEL Active Region (R)Evolution

Experimental diodes only; post-1989 → like edge-emitters'



EpiDesign – 504 Layers! (red added)



Grown by Jim Harbison and Leigh Florez

What was New and Crucial

1) High-R mirrors → thin active region

active region like edge-emitters'
low current → higher reliability

2) All-epitaxial (basically) semiconductor cavity

monolithic epi growth → manufacturability
thermal conductivity → higher temp, higher reliability

3) Graded-interface mirrors / conductive P-mirror

reduced electrical resistance, heating

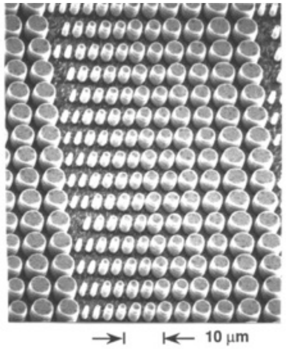
All these features are still in "all" commercial VCSELs

Features were "essential"

Stimulated industrial/university R&D and funding

Ludicrously small size, millions/cm^2 ?

NOT used, not likely to be used
caught peoples' attention + imagination
never underestimate the value of an image



How Could This Be?

Optics, Collaboration, Risk

Jack Jewell, Axel Scherer, Sam McCall, Yong Lee, Jim Harbison, Leigh Florez, and Hyatt Gibbs

Early VCSEL background

- **Various accounts of ideas, lasing, optically pumped lasing, etc in vertical cavity structures in the 70's and even 60's**
- **Isolated curiosities – no recognition or announcement of potential impact, hence no impact**
- **a couple notable exceptions**

Origin of VCSEL

JPN. J. APPL. PHYS. Vol. 18 (1979), No. 12

GaInAsP/InP Surface Emitting Injection Lasers

Haruhisa SODA, Ken-ichi IGA,
Chiyuki KITAHARA and Yasuharu SUEMATSU†

Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 227

† Department of Physical Electronics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152

(Received August 6, 1979)

A conventional injection semiconductor laser consists of two end mirrors perpendicular to the active layer,[1-3] so that, the light output is parallel to the wafer surface. If an injection laser with the light output perpendicular to the wafer surface could be obtained, it would be very easy to fabricate a laser array. In relation to this aim, a distributed Bragg reflector laser with 4th order grating can emit light perpendicular to the wafer surface.[4]

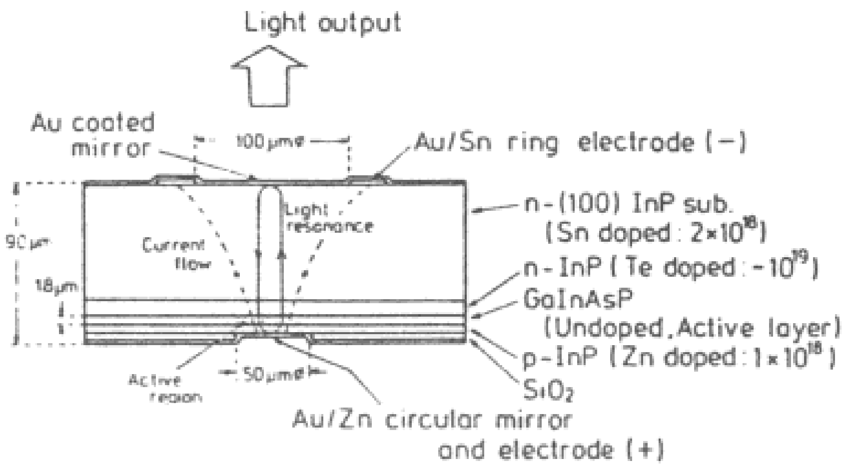


Fig. 1. Schematic structure of GaInAsP/InP surface emitting injection laser.

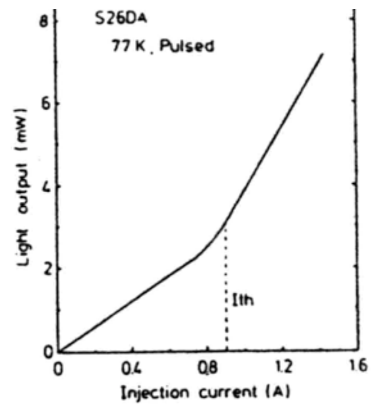


Fig. 3. Light output vs. injection current characteristic of a surface emitting injection laser.

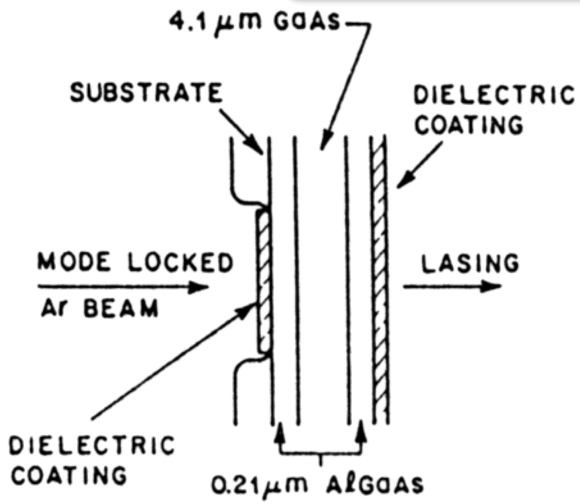
Another notable exception

- **Late 70's – people glued few-μm-thick films of GaAs between mirrors, zapped them with laser beams for lasing, or optical bistability – Bell Labs**
- **A move to U. Arizona Optical Sciences (Hyatt Gibbs)**

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-16, NO. 12, DECEMBER 1980

Ultrashort Laser: Lasing in MBE GaAs Layer with Perpendicular-to-Film Optical Excitation and Emission

A. PASSNER, H. M. GIBBS, A. C. GOSSARD, S. L. McCALL, T. N. C. VENKATESAN, AND W. WIEGMANN



Manuscript received January 26, 1979; revised July 2, 1980.

A. Passner, A. C. Gossard, S. L. McCall, T. N. C. Venkatesan, and W. Wiegmann are with Bell Laboratories, Murray Hill, NJ 07974.

H. M. Gibbs was with Bell Laboratories, Murray Hill, NJ 07974. He is now with the Optical Sciences Center, University of Arizona, Tucson, AZ 85721.

2nd VCSEL root

- **Optical Logic Devices → replace silicon IC technology**
  - **fundable, fun, interesting, classical/quantum optics**
  - **many PhD theses**
- **Glue MBE GaAs film between mirrors, or coat directly**
- **Optical Bistability (1st demonstration – Gibbs, McCall, Venkatesan)**
- **Optical Logic Gates – Jewell – using picosecond pulses, pump a GaAs etalon at one wavelength to shift the cavity resonance toward or away from the probe wavelength**
- **ALL-OPTICAL Devices**

3-pJ, 82-MHz optical logic gates in a room-temperature GaAs-AlGaAs multiple-quantum-well étalon

J. L. Jewell
AT&T Bell Laboratories, Holmdel, New Jersey 07733

Y. H. Lee, M. Warren, H. M. Gibbs, and N. Peyghambarian
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

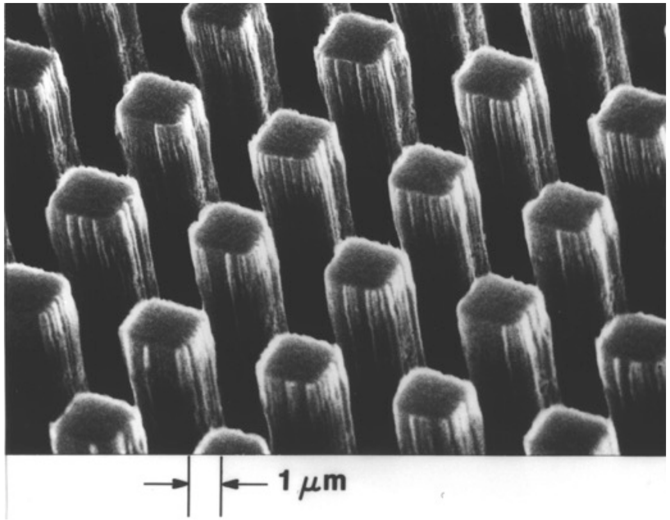
A. C. Gossard and W. Wiegmann
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 3 January 1985; accepted for publication 25 February 1985)

Politically incorrect collaboration with my former university advisor and across different Bell Labs locations

Epitaxial Semiconductor Optics

- Glued dielectric mirrors → epitaxial GaAs/AlAs
  - manufacturability, uniformity, heat, electrical current
- Planar structure → microresonator
  - optical/electrical confinement
  - high density



GaAs-AlAs monolithic microresonator arrays

J. L. Jewell
AT&T Bell Laboratories, Holmdel, New Jersey 07733

A. Scherer
Bell Communications Research, Red Bank, New Jersey 07701

S. L. McCall, A. C. Gossard, and J. H. English
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Politically incorrect collaboration with Bellcore

Idea credit

(Received 8 April 1987; accepted for publication 12 May 1987)

Monolithic optical logic devices 1.5–5 μm across are defined by ion-beam assisted etching through a GaAs/AlAs Fabry–Perot structure grown by molecular beam epitaxy. They show reduced energy requirements (more than an order of magnitude smaller than the unetched heterostructure), uniform response over small arrays, negligible crosstalk at 3 μm center-center spacing, ~150 ps recovery time, and thermal stability at 82 MHz operating frequency. All experiments were performed at room temperature.

Epitaxial MBE-grown mirrors 1st shown by Illegems, Van der Ziel (1975)

How High Can the Reflectivity Be?

- **90% mirrors → ~99% reflectivity**
- **thinner active material → <u>lower energy to activate</u>**
- **No indication that this was an upper limit!**

High-finesse (Al,Ga)As interference filters grown by molecular beam epitaxy

J. L. Jewell and Y. H. Lee
AT&T Bell Laboratories, Room 4G-520, Holmdel, New Jersey 07733

S. L. McCall
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

J. P. Harbison and L. T. Florez
Bell Communications Research, Red Bank, New Jersey 07701-7020

(Received 11 May 1988; accepted for publication 17 June 1988)

We have measured finesse values of at least 160 in (Al,Ga)As Fabry–Perot interference filters grown by molecular beam epitaxy. Losses are low and the finesses are close to predicted values, suggesting that with additional mirror layers much higher finesse should be achievable. This has important implications in the development of resonator-based low-energy photonic logic devices and lasers for information processing and communication. Formulas for calculating the finesse and other parameters such as the effective optical thickness of the cavity in such structures are also given.

as the nonlinear medium. It should be possible to construct lasers or modulators for chip-to-chip communication with very low activation energies by taking advantage of such high finesse in microresonators.

640 Appl. Phys. Lett. **53** (8), 22 August 1988

UCSB - Periodic gain

Conference on Lasers and Electro-Optics, Anaheim, CA

Wednesday **AFTERNOON**

27 April 1988 **WM**

PACIFIC BALLROOM A/B

1:00 PM Poster Session: 2

SEMICONDUCTOR DIODE LASERS

WM1 Analysis and design of a novel parallel-driven MQW-DBR surface-emitting diode laser

R. GEELS, R. H. YAN, J. W. SCOTT, S. W. CORZINE, R. J. SIMES, LARRY A. COLDREN, UC–Santa Barbara, Electrical & Computer Engineering Dept., Santa Barbara, CA 93106.

Efficient surface-emitting lasers are desired for applications in optical signal processing, communication, IC interconnection, and computing.

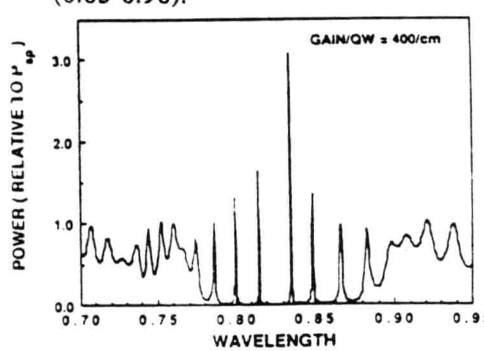
LEOS'88, Santa Clara, CA #OE1.2

SURFACE-EMITTING-LASERS WITH PERIODIC GAIN

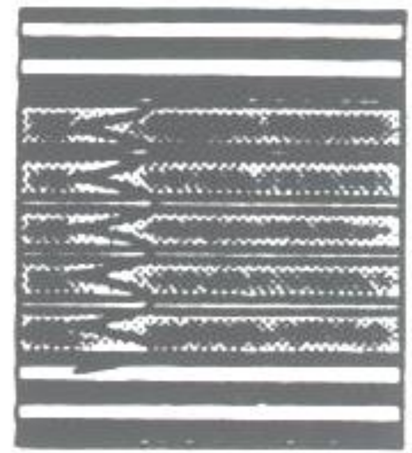
S. W. Corzine, R. S. Geels, J. W. Scott, and L. A. Coldren

University of California, Santa Barbara, CA 93106

We present here the concept of periodic gain in the design of DBR Surface-Emitting Lasers. We analyse and compare our new periodic gain configuration with two typical standard Fabry-Perot structures and show that significant advantages can be obtained. Aside from the inherent mode selectivity obtained with periodic gain, we find that the threshold current can be reduced by a factor of two over standard structures for reasonable ranges of mirror reflectivities (0.85-0.98).



WM1 Fig. 3. (a) Transmission through cavity for an assumed flat gain below threshold indicating mode enhancement due to periodic gain. (b) Cavi-



case a

SQW VCSEL, optically pumped

- 99% → 99.9% reflectivity
  - thinner active material → lower current density
- 60 QWs → 20 QWs → 9 QWs (RPG) → 3 QWs → 1 QW
  - took ~1 week for this optically-pumped progression
- Announced March 1989 at Photonic Switching

Vertical cavity single quantum well laser

J. L. Jewell, K. F. Huang,[a] K. Tai,[b] Y. H. Lee, R. J. Fischer,[b] S. L. McCall,[b] and A. Y. Cho[b]
AT&T Bell Laboratories, Room 4G-520, Holmdel, New Jersey 07733

(Received 15 February 1989; accepted for publication 19 May 1989)

We have achieved room-temperature pulsed and cw lasing at 980 nm in an optically pumped vertical cavity structure grown by molecular beam epitaxy containing only a single quantum well (SQW) of $In_{0.2}Ga_{0.8}As$. Limited gain due to the extremely short active material length c 80 Å implies that losses due to absorption, scattering, and mirror transmission are extremely low. Using 10 ps pump pulses at 860 or 880 nm, the estimated energy density absorbed in the spacer was ~ 12 fJ/μm^2 at threshold, indicating a carrier density approximately four times that required for transparency. Continuous wave pumping yielded an estimated threshold absorbed intensity of ~ 7 μW/μm^2.

cross-sectional area divided by finesse. A 1-μm-diam SQW microlaser electrically pumped would have a current threshold $< 10 \mu$A if cavity losses and surface recombination are kept low.

Appl. Phys. Lett. **55** (5), 31 July 1989

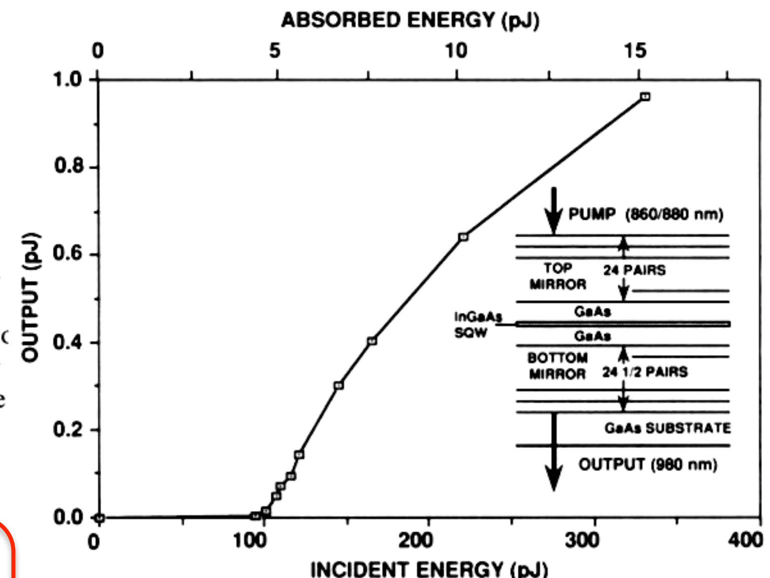


FIG. 1. Output through the bottom mirror vs incident input and esti absorbed input for pulsed pumping at 860 nm. Inset: schematic of the grown SQW resonator.

Getting Current through P-Mirror

- **Optically-pumped → electrically-pumped**
  - **ohmic contact, dope the mirrors but avoid absorption!**
  - **superlattice-graded interfaces → lower resistance**

Extremely low resistance nonalloyed ohmic contacts on GaAs using InAs/InGaAs and InAs/GaAs strained-layer superlattices

C. K. Peng, G. Ji, N. S. Kumar, and H. Morkoç
University of Illinois, Coordinated Science Laboratory, 1101 West Springfield Avenue, Urbana, Illinois 61801

(Received 22 April 1988; accepted for publication 29 June 1988)

Employing a structure consisting of n^+-InAs/InGaAs and InAs/GaAs strained-layer superlattices (SLS's) grown by molecular beam epitaxy on GaAs films, nonalloyed contact resistances less than 8.5×10^{-8} Ω cm^2 have been obtained. Self-consistent simulations show that these extremely small nonalloyed contact resistances are due to the suppression of the depletion depth in the GaAs channel and tunneling through the SLS layer. Similar structures on InGaAs channels have led to nonalloyed specific contact resistances of about 1.5×10^{-8} Ω cm^2. These results represent the smallest figures reported for these important material systems.

900 Appl. Phys. Lett. **53** (10), 5 September 1988 00(

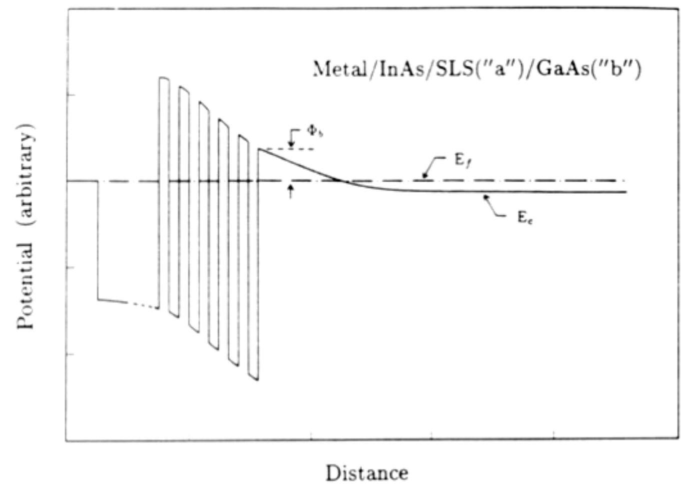
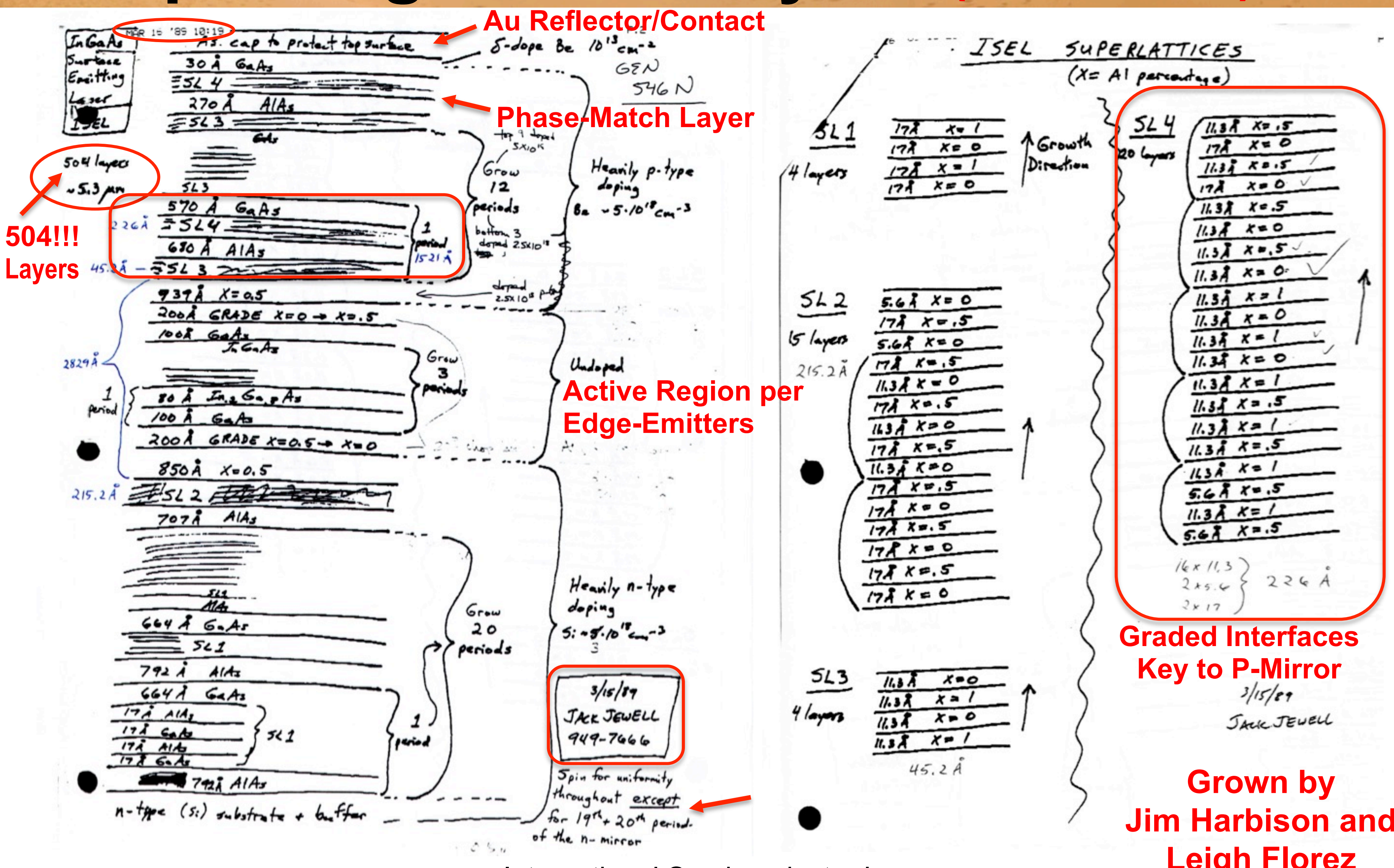


FIG. 2. Schematic representation of the conduction-band profile. The lowering of the bulk barrier height (Φ_b) due to the strained-layer superlattice (SLS) is clearly shown.

EpiDesign – 504 Layers (red added)



Nexus – put it all together

LOW-THRESHOLD ELECTRICALLY PUMPED VERTICAL-CAVITY SURFACE-EMITTING MICROLASERS

Indexing terms: Semiconductor lasers, Quantum optics

Vertical-cavity electrically driven lasers with three GaInAs quantum wells and diameters of several μm exhibit room-temperature pulsed current thresholds as low as 1·3 mA with 958 nm output wavelength.

Vertical-cavity surface-emitting lasers[1–3] show promise for a variety of applications. The lowest threshold edge-emitting

J. L. JEWELL
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Y. H. LEE
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19th June 1989

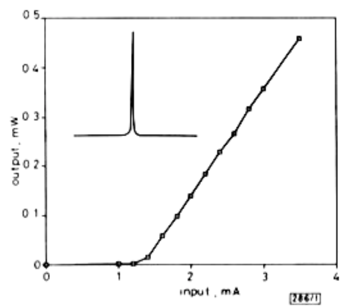
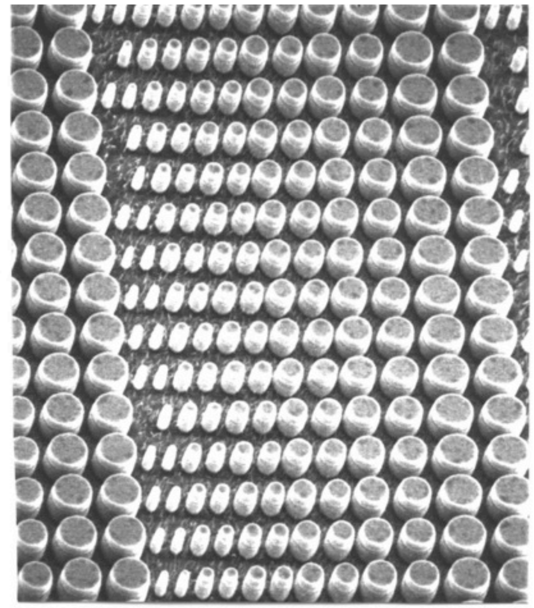


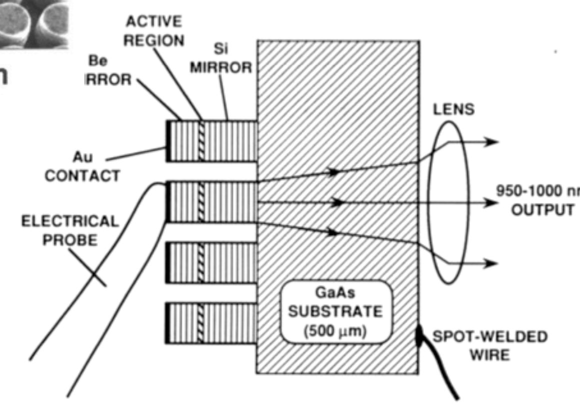
Fig. 1 *Output light power against current*
Differential quantum efficiency is about 16%. Inset shows typical spectrum at 1·6 mA for a 3 μm diameter microlaser. Peak full width at half-maximum is about 4 Å, the spectrometer resolution. Trace spans from 9300 to 9845 Å

ELECTRONICS LETTERS 17th August 1989 Vol. 25 No. 17 pp. 1123-1124



Axel Scherer: 1-etch process

Worked on 1st try!!



Announced July 1989 at IOOC in Japan

Room-temp CW SQW VCSEL

Etched only halfway down → improved heatsinking → CW

ROOM-TEMPERATURE CONTINUOUS-WAVE VERTICAL-CAVITY SINGLE-QUANTUM-WELL MICROLASER DIODES

Indexing terms: Semiconductor lasers, Quantum optics, LEDs

Room-temperature continuous and pulsed lasing of vertical-cavity, single-quantum-well, surface-emitting microlasers is achieved at ~983 nm. The active $Ga_{0.8}In_{0.2}As$ single quantum well is 100 Å thick. These microlasers have the smallest gain medium volumes among lasers ever built. The entire laser structure is grown by molecular beam epitaxy and the microlasers are formed by chemically assisted ion-beam etching. The microlasers are 3–50-μm across. The minimum threshold currents are 1·1 mA (pulsed) and 1·5 mA (CW).

Y. H. LEE
J. L. JEWELL
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S. L. McCALL†
J. P. HARBISON*
L. T. FLOREZ*

21st July 1989

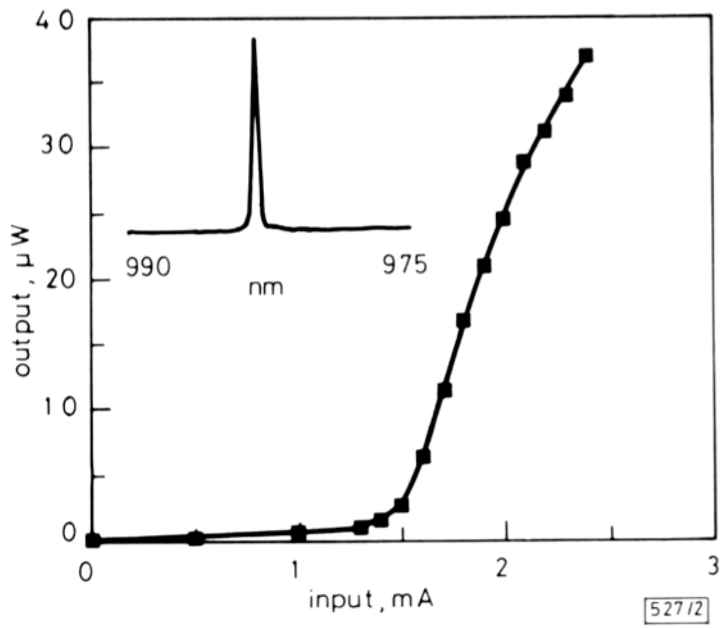


Fig. 2 *Output against current for 5 μm-square microlaser operating CW at room temperature without heat-sinking*

Inset shows spectrum at 1·8 mA. Spectral line width is 3·5 Å, the resolution limit of spectrometer

Optical Sciences grads at Bell Labs
drove early 90’s commercialization

Though we hadn’t built lasers,
VCSELs were like new / old friends

- **Yong Lee – 850nm top-emitting VCSEL (proto-commercial VCSEL architecture)**
- **Kuochou Tai – co-founded TrueLight Photonics**
- **Bob Morgan – key practical developments @ Bell Labs, went to Honeywell to develop 1st VCSEL products**

What Followed Quickly Afterward

United States –

- DARPA quickly provided large VCSEL funding to
  - AT&T Bell Labs
  - Honeywell → Finisar
  - HP → Agilent → Avago
  - Many universities, especially UC Santa Barbara
  - Startups like Photonics Research (Vixel), Optical Concepts
- Bellcore, Motorola started large internally-funded efforts

Largest VCSEL suppliers (datacom)

Japan –

- NEC and other companies quickly started developments

Europe –

- Infineon – parallel interconnect
- Universities (Ulm) and Research Institutes

ULM Photonics → Philips - Large VCSEL supplier (non-datacom)

DARPA view

A Historical Perspective of the Development of the Vertical-Cavity Surface-Emitting Laser

Elias Towe, Robert F. Leheny, *Fellow, IEEE*, and Andrew Yang

electronics. From 1988 to 1993, Yang served as a program manager for optoelectronics at the Advanced Research Projects Agency (DARPA).

emitting lasers [13]. Jewell *et al*. [14] introduced quantum-well structures into the active regions of short wavelength (0.9 m) GaAs-based surface-emitting lasers. Exploiting what at the time was a better developed materials system, this group was able to simultaneously achieve low-resistance electrical contracts and high-reflectivity mirrors, which resulted in room-temperature, continuous-wave, and ultimately low-threshold current density operation with only a single quantum well, properly positioned in the active region of the laser structure [15]. This demonstration marked a turning point in the development of the surface-emitting laser. Several more research groups entered the field, and many important innovations were soon being reported from all over the world.

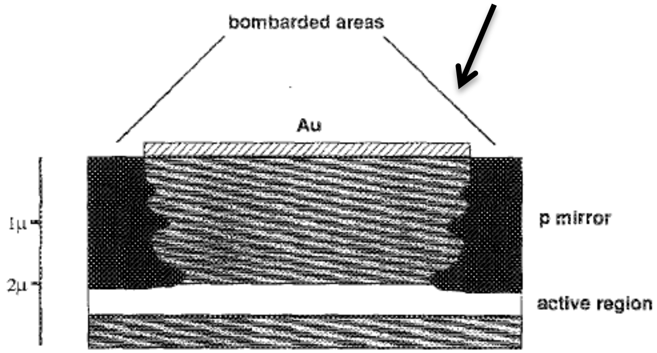
IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000

Important Innovations

These advances enabled Gigabit Ethernet VCSELs

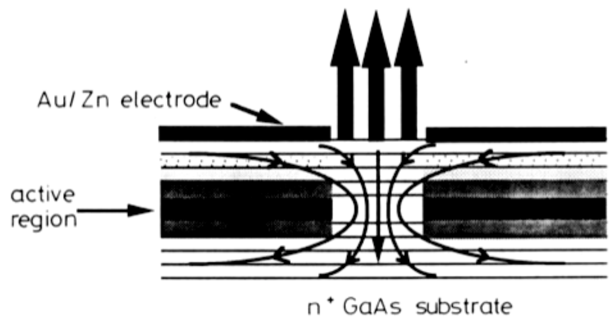
Ion-Implanted Planar VCSEL (heat diss., manufacturable) 1989

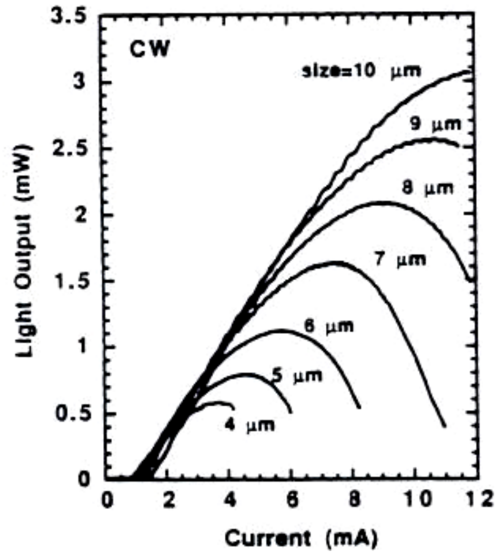
Bell Labs (MH) **Bellcore**



Top-emitting 850nm (commercial architecture) 1990

Bell Labs (HL)





Large-scale reliability study/development and manufacturing early 1990's

Honeywell

Gain Offset for Temp Stability; Gain/Power Optimization 1990

University of California Santa Barbara

Gigabit Ethernet

THE crucial 1st large VCSEL application

Final approval June 25, 1998, but started much earlier

Once again, Fibre Channel provided the starting point for the 1000BASE-SX specification, but in addition, the 1000BASE-SX specification embraces VCSELs as well as the older CD style of laser developed for the Fibre Channel market.

- Howard Frazier, Chair of the Gigabit Ethernet Task Force

Optics

Del Hanson, HP (408) 435-6246		H.P.
Jonathan Thatcher, IBM (507) 253-2867		IBM
Stan Swirhun, VIXEL (303) 460-0700 x17		VIXEL

Update to Joint Proposal of May, 1995

IEEE 802.3z
Gigabit Ethernet

Slide 1 September 09, 1996

Sept 9, 1996

Slide # 21: "Summary of Optical Link Specification Recommendations"
+ Reduce the spectral width of the 770-860 nm LD source at 2 nm rms to accommodate future lower threshold VCSELs

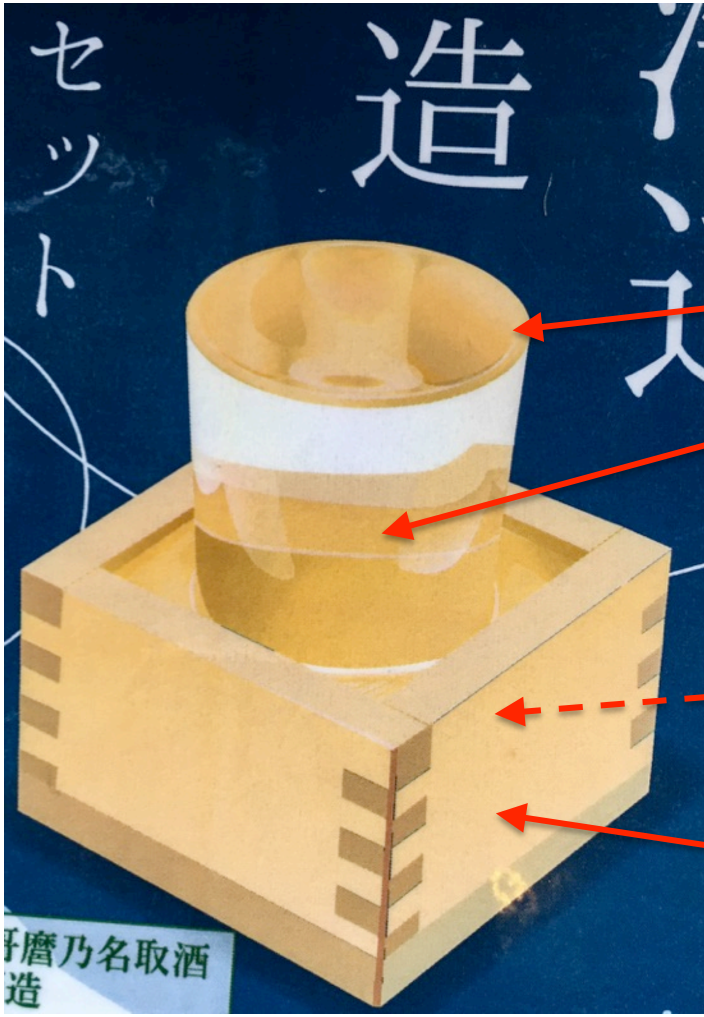
Window of Opportunity

- Gigabit Ethernet – Huge Window of Opportunity for VCSEL
- Barely-commercially-viable 1.25Gb/s VCSELs in mid-90's from Honeywell, HP, Vixel
- IBM/Rohm had developed reliable CD lasers
- VCSELs won the GigE and F-C business, which fueled VCSELs for high-volume commercialization
- It took an intensive effort throughout the early 1990's to develop those VCSELs
- DARPA initiated enabling funding for VCSEL development, starting 1989, following this VCSEL advance
- Missed windows of opportunity are devastating to a business

Conclusions

- **Key innovations in this 1989 VCSEL advance are still used in essentially all commercial VCSELs**
  - **>99% reflecting mirrors and thin active regions**
  - **Essentially-all-epitaxial structures**
  - **P-mirror with graded interfaces**
- **It resulted from optics emphasis, great collaboration, and taking risks**
- **These advances stimulated stimulated worldwide funding and R&D, especially through DARPA**
- **The DARPA-funded companies developed commercially-viable VCSELs “just in time” to meet the Gigabit Ethernet window of opportunity, and enact high-volume VCSEL business**

Any Questions?



Vertical-Cavity Slosh-Effective Liquid

Output Coupler

Active Material (Caution! Organic dopants may induce nonlinear behavior!)

Bottom Mirror (100% reflecting, hidden within substrate)

Substrate