Research at Sandia National Laboratories in Optical Interconnects

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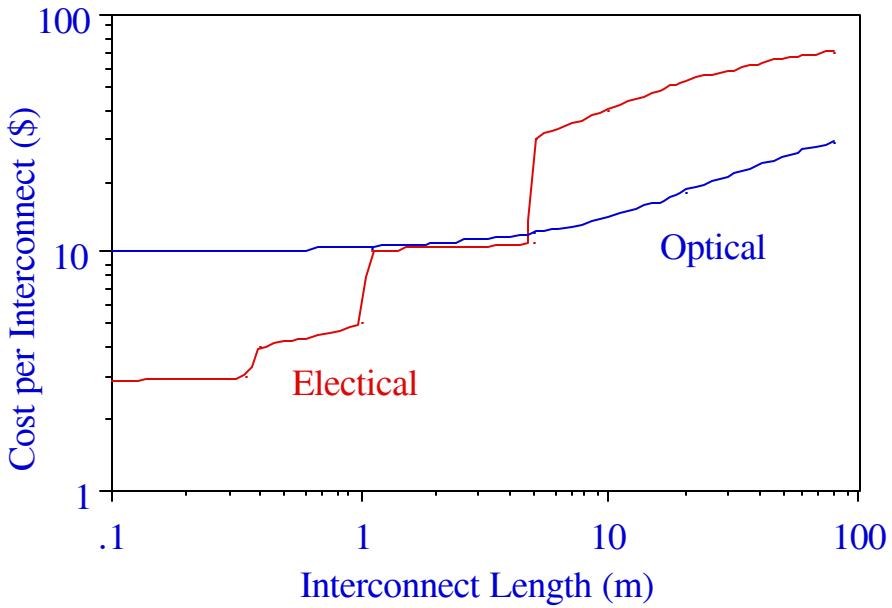
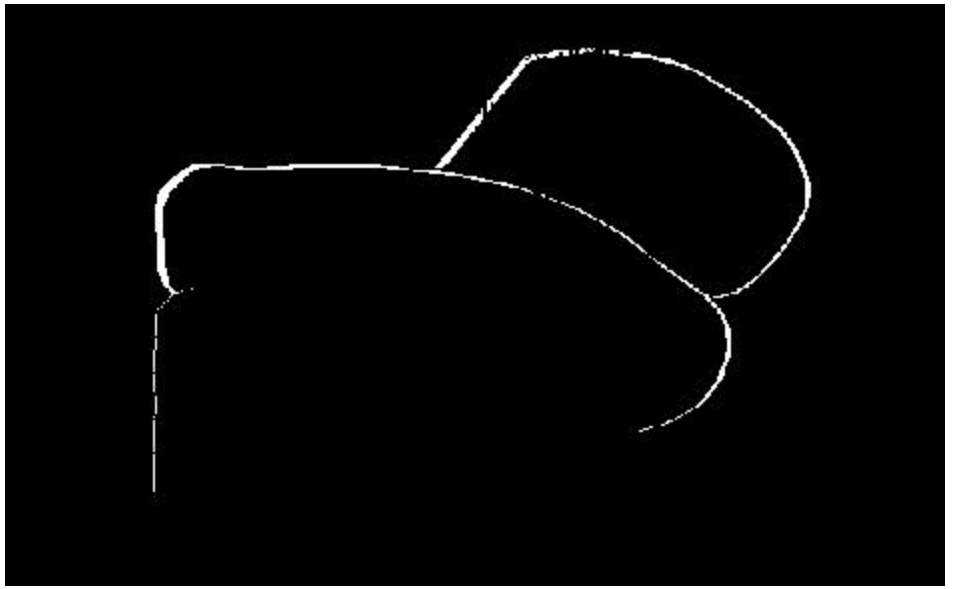
Kent D. Choquette -- VCSELs

Introductory overview
VCSEL device performance
VCSEL array performance
VCSEL integration
Photodetector performance, arrays, integration

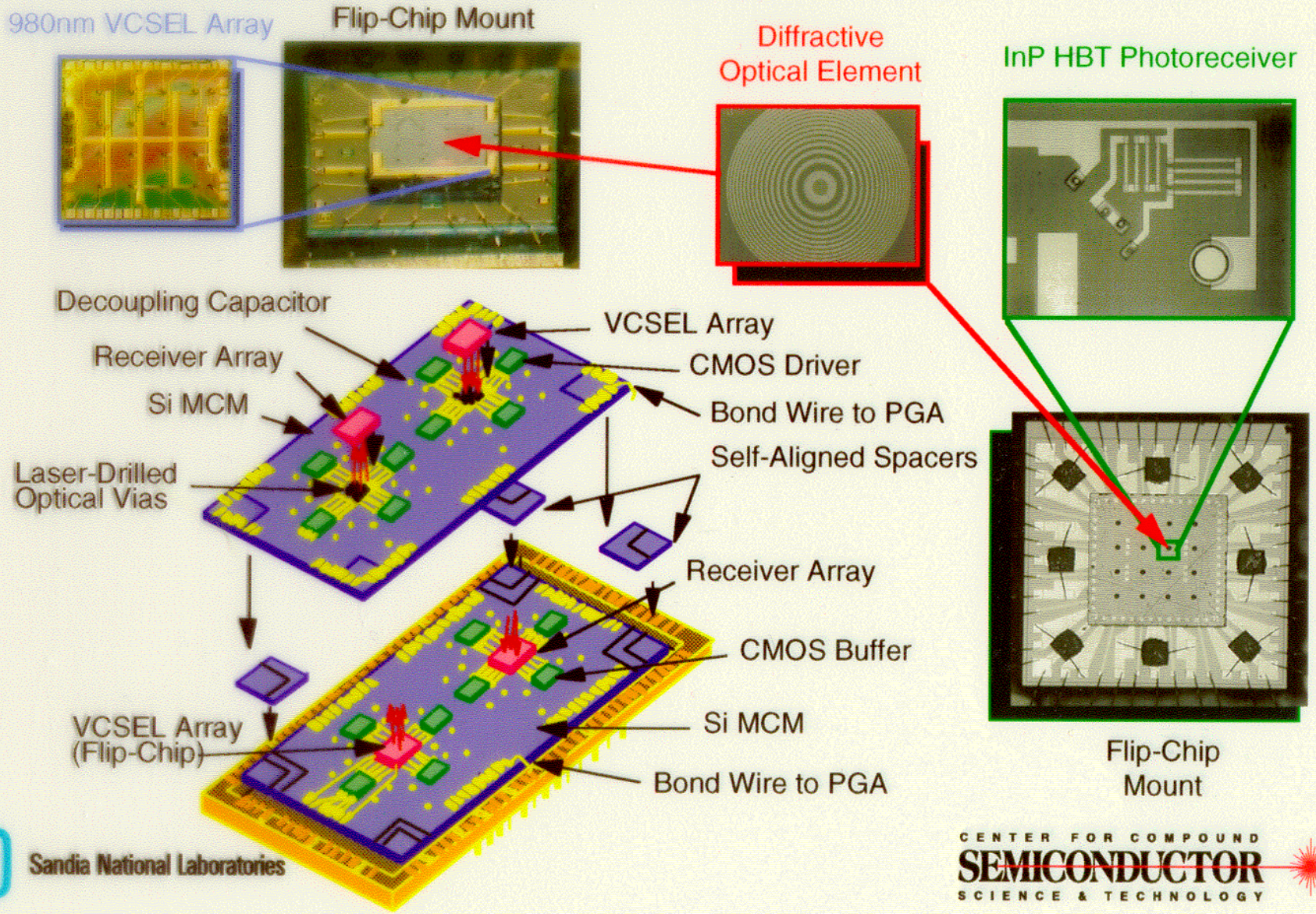
VCSELs Enable Data Communication Applications

- High volume/low cost manufacture for inexpensive optical links
- 2-Dimensional VCSEL arrays for high density interconnects





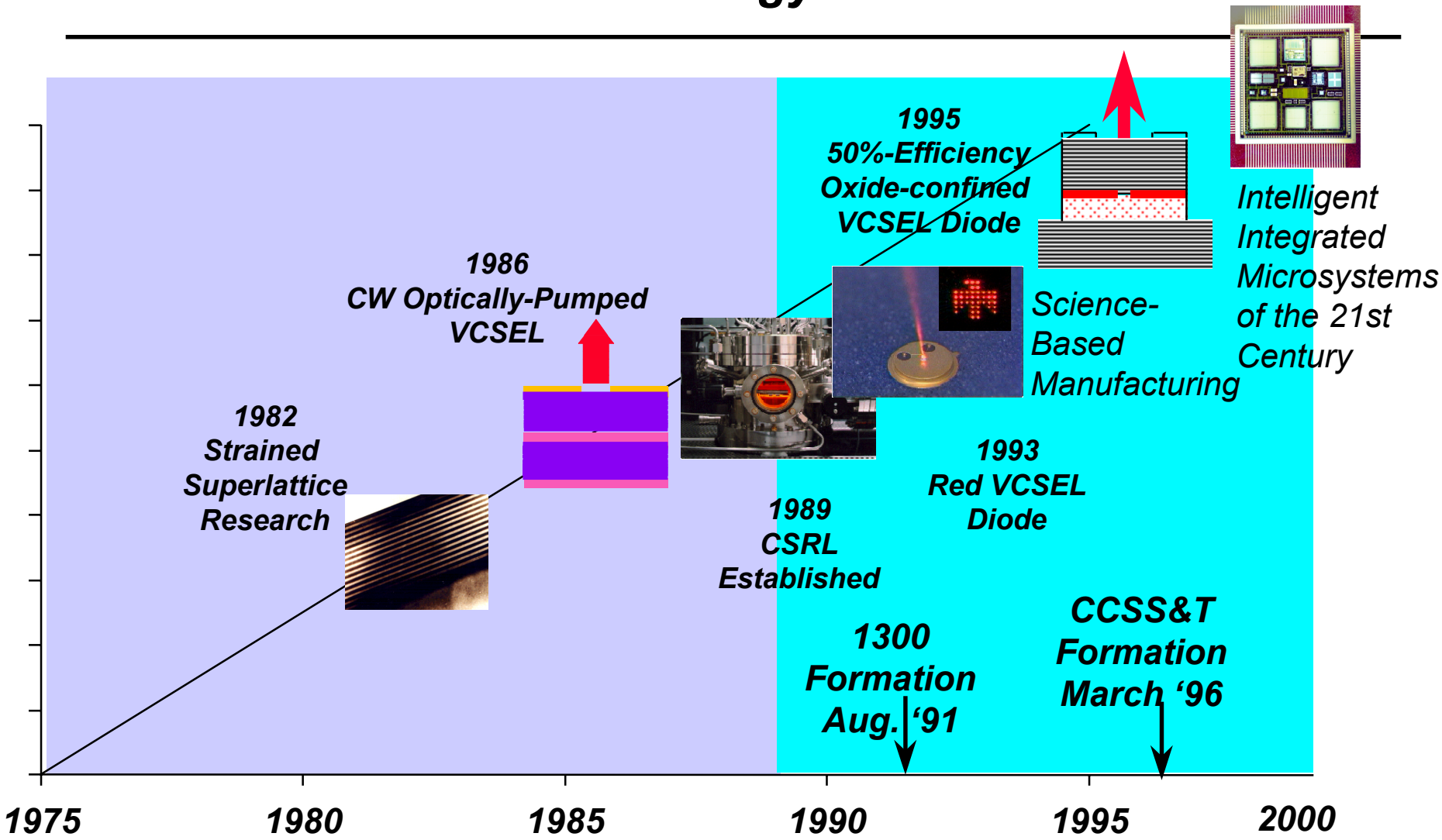
Free-Space Photonic Interconnects are Being Prototyped for Board-to-Board Communications



Sandia National Laboratories

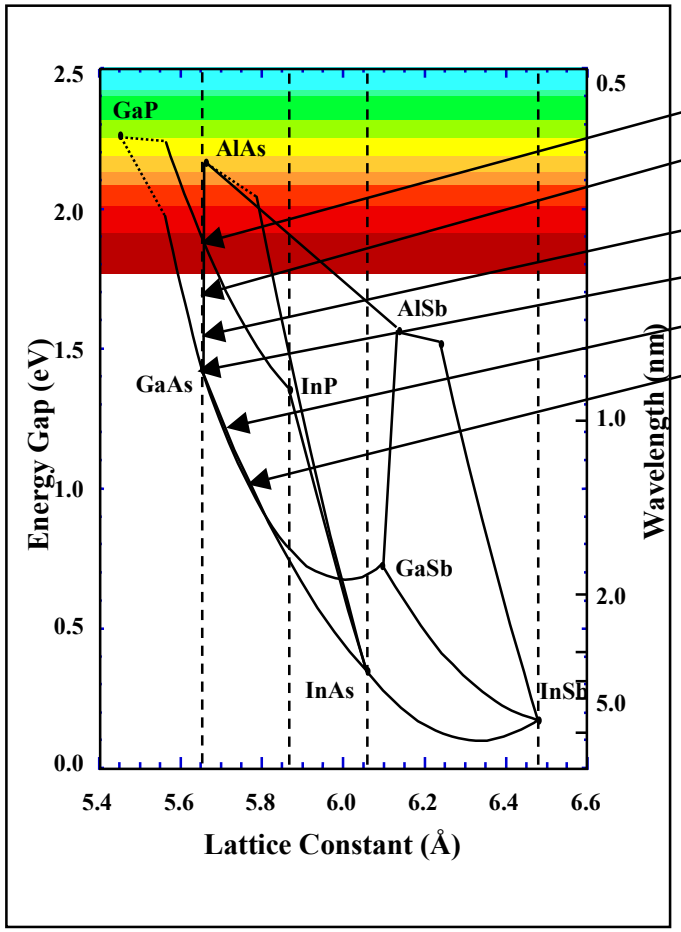
CENTER FOR COMPOUND SEMICONDUCTOR SCIENCE & TECHNOLOGY

The CCSS&T Has Evolved from Roots of Material Science to Provide Relevant Technology to Address DOE Needs

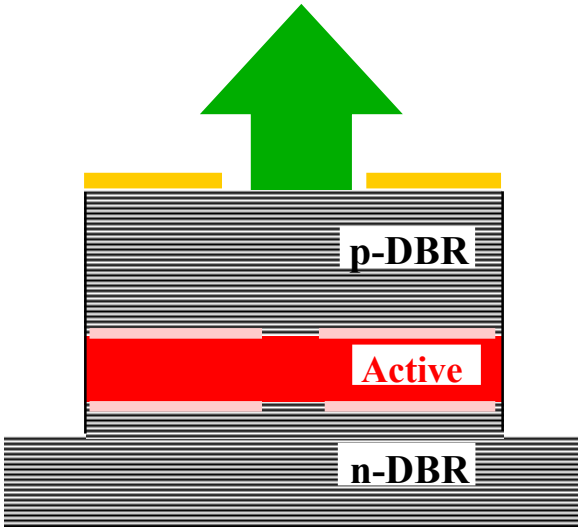


20 Years of Investment in Science and Technology

VCSEL Wavelength and Material Structures at Sandia



VCSEL	Active Layer	Barrier	High-n	Low-n DBR
650 nm	InGaP	InGaAlP	$Al_{0.5}Ga_{0.5}As$	$Al_{0.96}Ga_{0.04}As$
700 nm	$Al_{0.24}Ga_{0.76}As$	$Al_{0.4}Ga_{0.6}As$	$Al_{0.4}Ga_{0.6}As$	$Al_{0.96}Ga_{0.04}As$
780 nm	$Al_{0.12}Ga_{0.88}As$	$Al_{0.35}Ga_{0.65}As$	$Al_{0.25}Ga_{0.75}As$	$Al_{0.94}Ga_{0.06}As$
850 nm	GaAs	$Al_{0.2}Ga_{0.8}As$	$Al_{0.16}Ga_{0.84}As$	$Al_{0.92}Ga_{0.08}As$
980 nm	$In_{0.19}Ga_{0.81}As$	GaAs	GaAs	$Al_{0.92}Ga_{0.08}As$
1060 nm	$In_{0.27}Ga_{0.73}As$	$GaAs_{0.7}P_{0.3}$	GaAs	$Al_{0.94}Ga_{0.06}As$



17-25 top DBRs

$Al_{0.98}Ga_{0.02}As$ oxidation layer

1λ cavity w/ 3QWs

35 bottom DBRs

(100) GaAs substrate

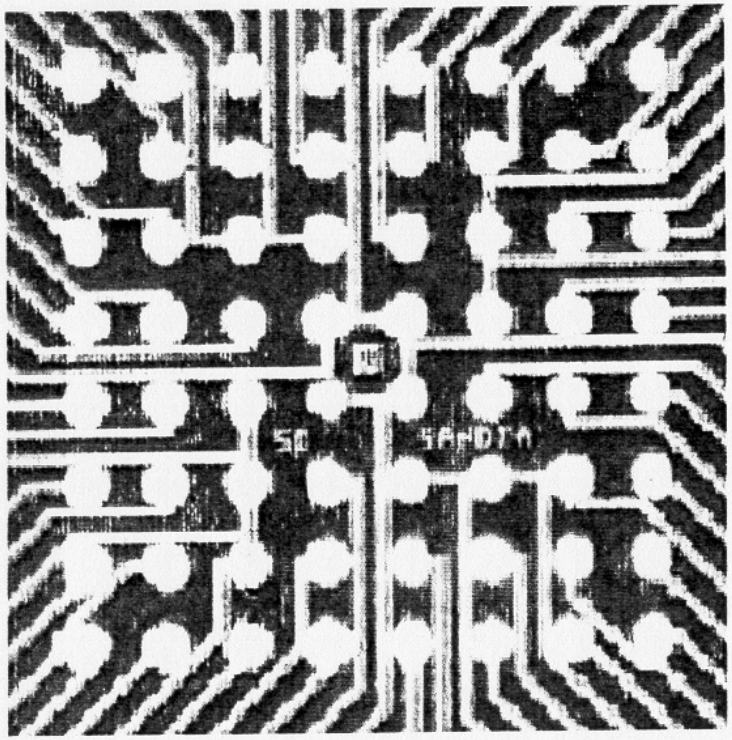
VERTICAL-CAVITY SURFACE-EMITTING LASERS OFFER ADVANTAGES OVER CONVENTIONAL DIODE LASERS

PERFORMANCE ADVANTAGES

- Surface-Normal Output
- Circular Output Beams
- Low Beam Divergence
- Small Active Volumes
- Low Threshold Currents
- Single Longitudinal Frequency
- Thermally Stable Operation
- High-Speed Modulation
- 2-Dimensional Arrays

MANUFACTURING ADVANTAGES

- On-Wafer Testing
- Ease of Integration
- Amenable to Mass Production
  High Volume/High Density



- Fabrication Based on Inexpensive Microelectronics Technology

Partial List of VCSEL Manufacturers

Large Companies

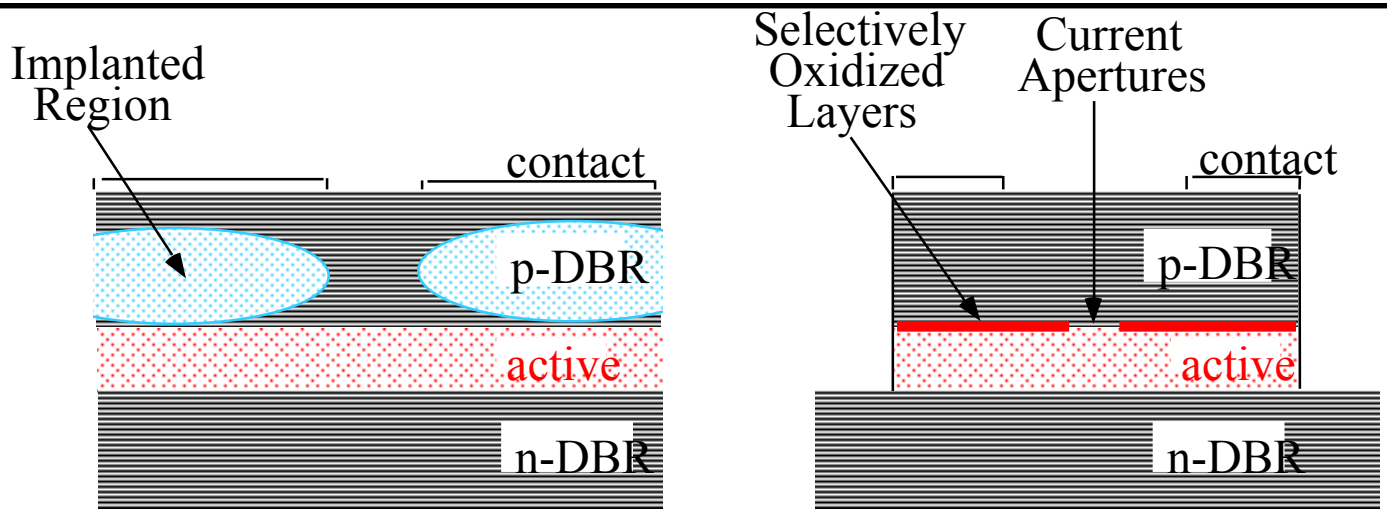
Hewlett Packard	data com. modules	850 nm
Honeywell	data com. modules, components	850 nm
Motorola	data com. modules (discontinued)	850 nm
Siemens (Germany)	data com. modules	850 nm
Mitel (Sweden)	data com. modules, components	850 nm
NEC (Japan)	2-D arrays (discontinued)	980 nm
Samsung (Korea)	data com. modules, optical read heads	850, 780 nm

Small Companies

Micro Optical Devices	components, sub assemblies	850 (670) nm
Cielo Communications	data com. modules	850 nm
Gore Photonics	data com. modules	850 (1300) nm
PicoLight	components	850 nm
Spire	components, wafers	850, 780 nm
EPI (UK)	wafers	850 (670) nm
True Light (Taiwan)	components	850 nm
Roithner Laser (Austria)	components	850 nm

- **850 nm (GaAs band edge) with a few GHz bandwidth is typical (local area data-com).**
- **Due to a lack of market, multi-GHz VCSELs are only available as “special orders” from some vendors.**

VCSEL Device Structure Developments

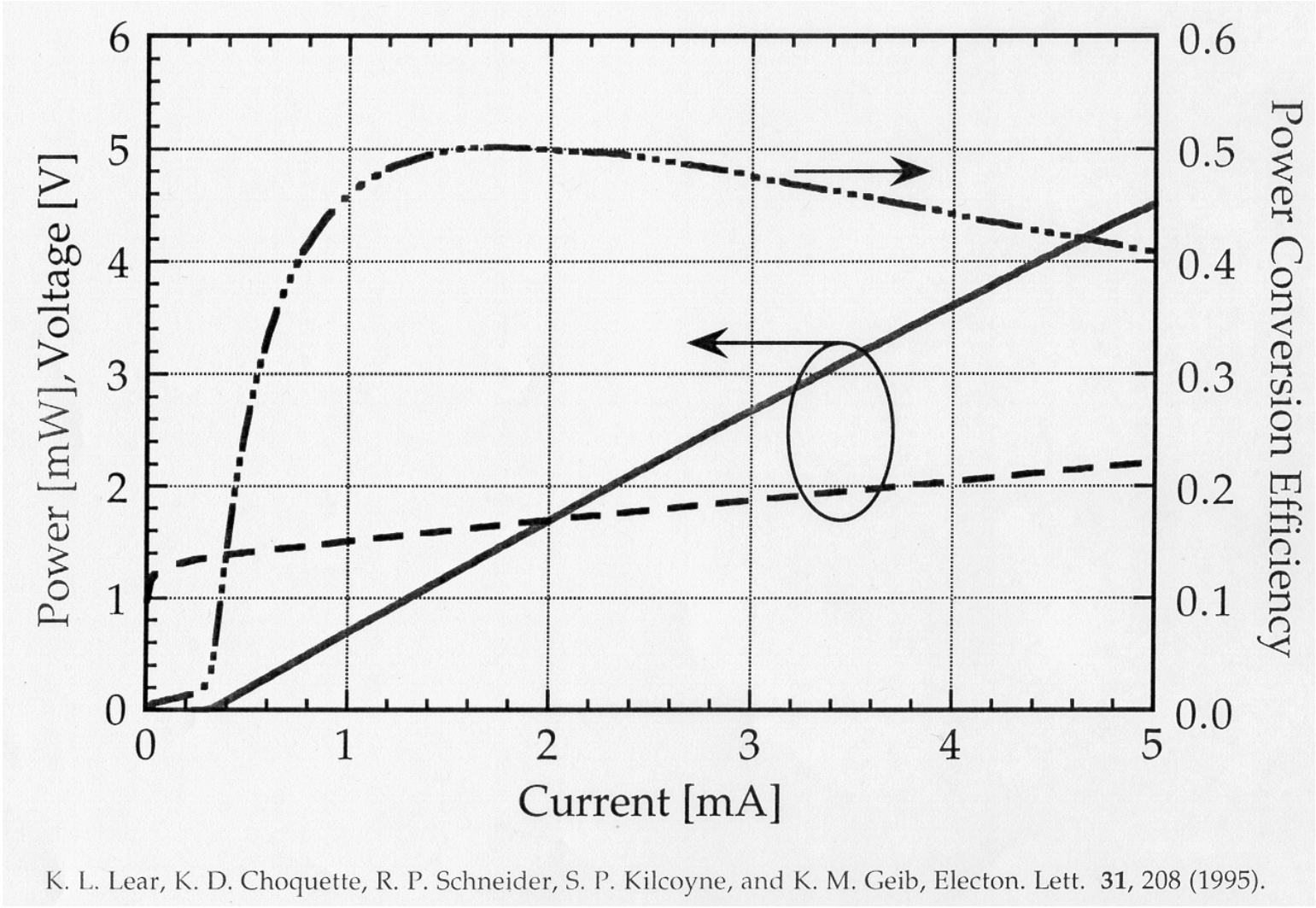


Implanted VCSEL ***Oxidized VCSEL***

Recent Advancements

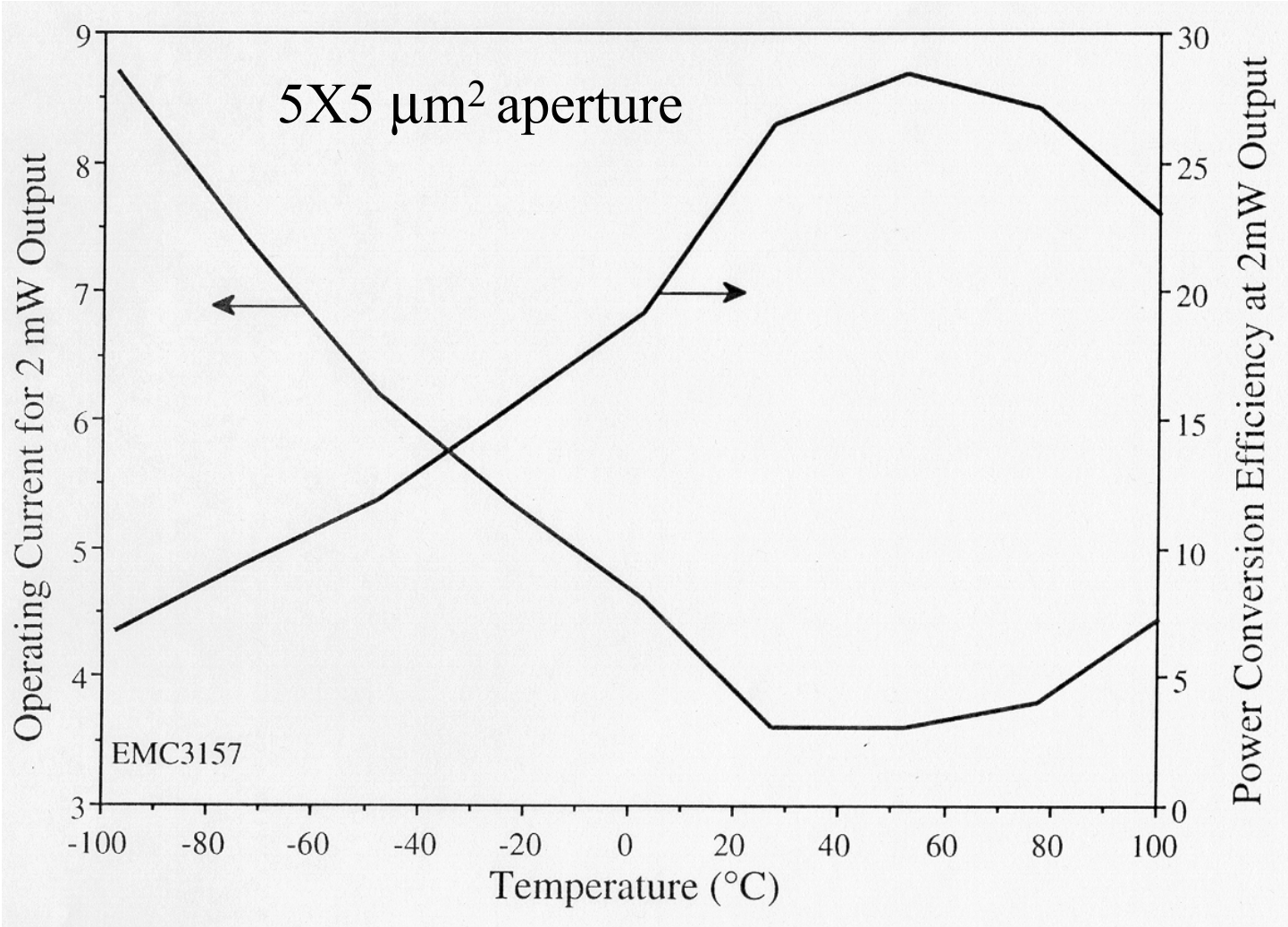
- **Alloy graded mirrors**
  - Mirror heterojunctions result in high normal resistance
  - Alloy grading significantly lowers resistance
- **Selective oxidation process**
  - Localizes carrier injection
  - Index guides light

Selectively Oxidized VCSELs Achieve 50% Efficiency at 1 mW Output Power

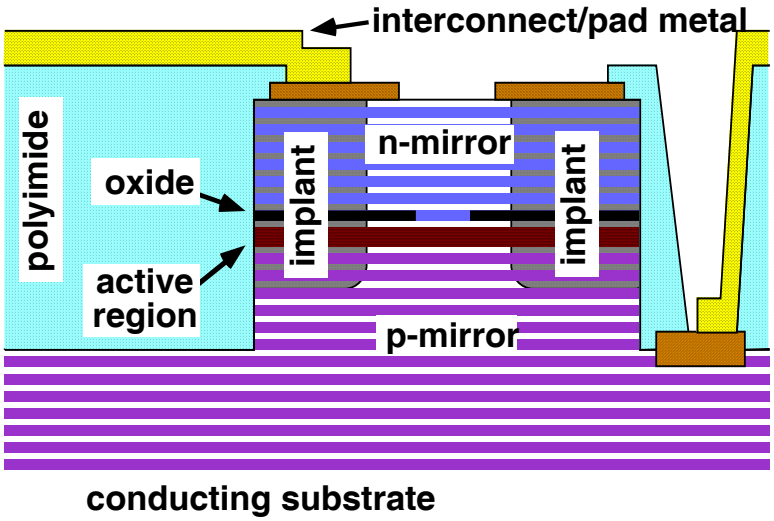


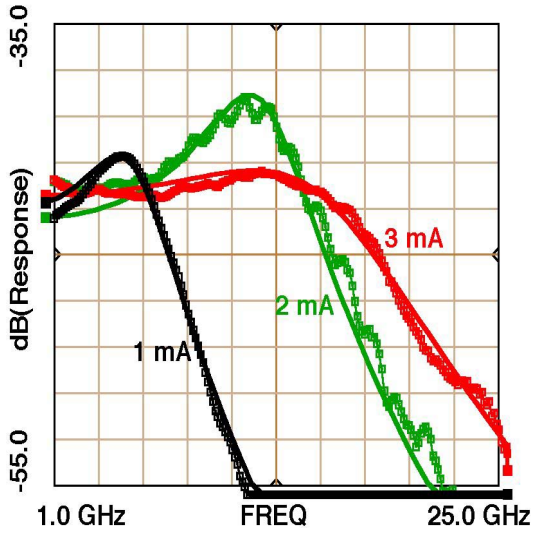
K. L. Lear, K. D. Choquette, R. P. Schneider, S. P. Kilcoyne, and K. M. Geib, Electon. Lett. **31**, 208 (1995).

Temperature Dependence of Selectively Oxidized VCSELs



High Speed VCSEL Results





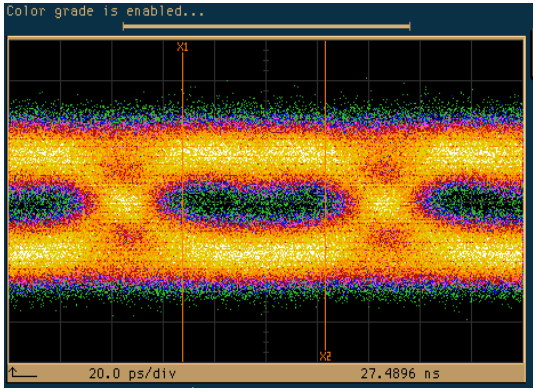
Excellent mode confinement and pump overlap provided by wet thermal oxidation

Low series resistance

- uniparabolic grading by MOVPE
- n-type up design

Low capacitance

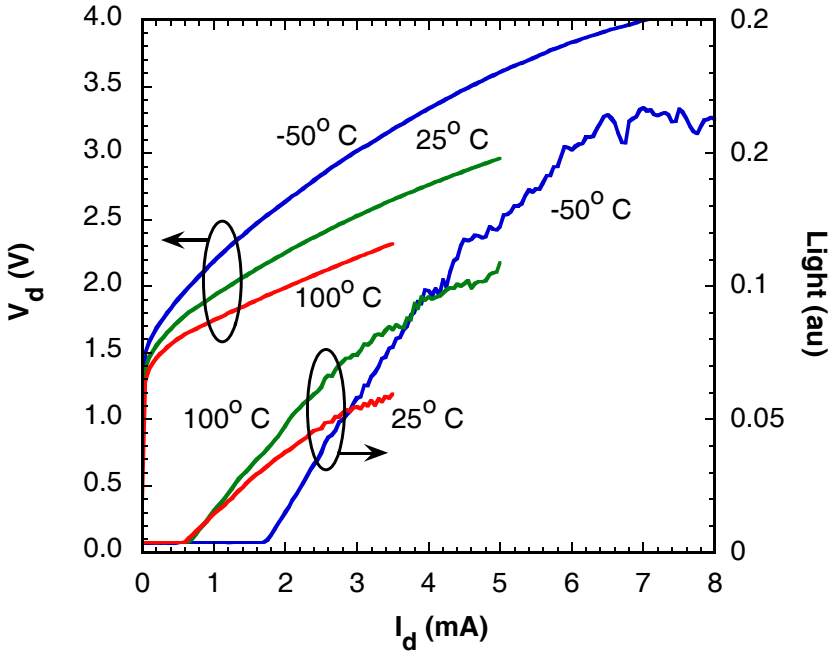
- proton implant under contact regions
- thick polyimide under contact pads

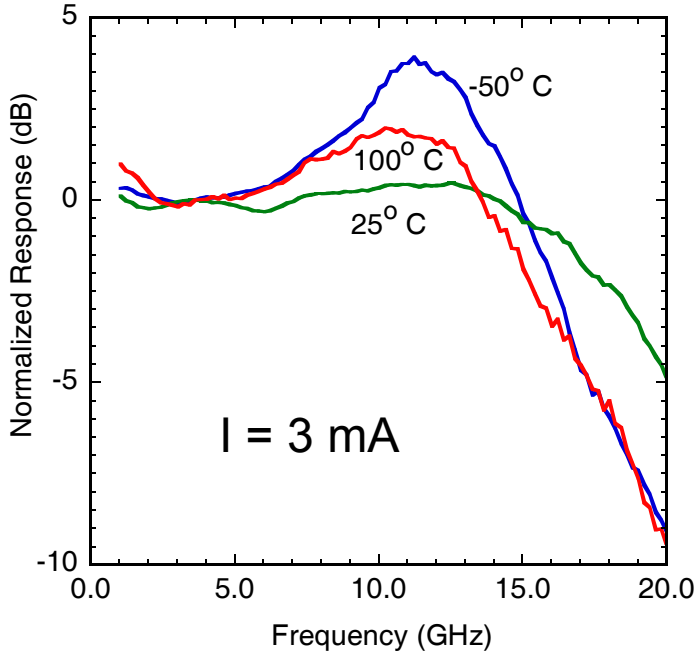


10 Gbps
ECL Levels
50Ω Drive
3mA DC Bias

Eye closure is due primarily to electrical noise

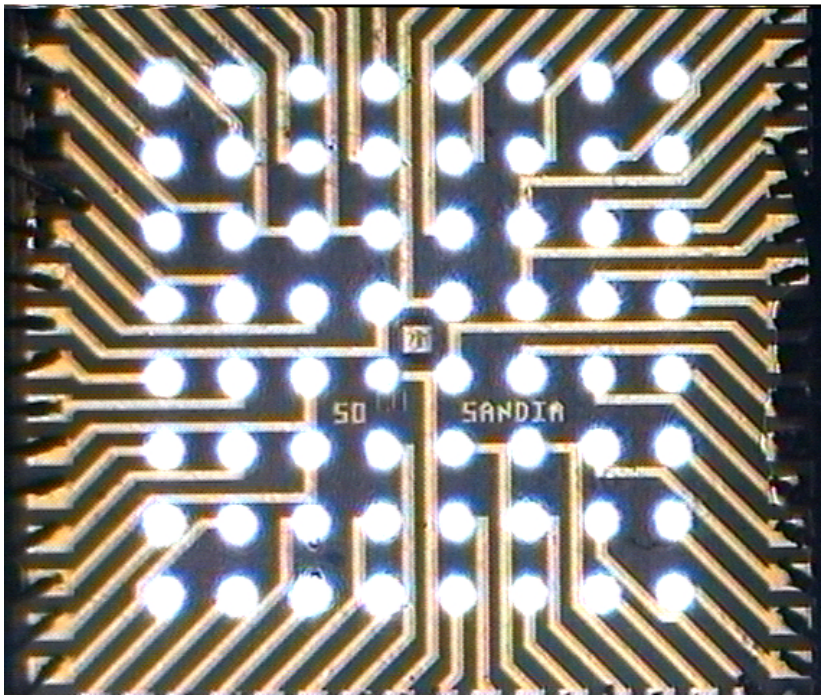
Temperature Effects





- **Both diode voltage and threshold current increase at low temperatures**
  - due to increased mirror resistance and cavity-gain misalignment
- **High bandwidth maintained over -50° to +100 C ° range.**

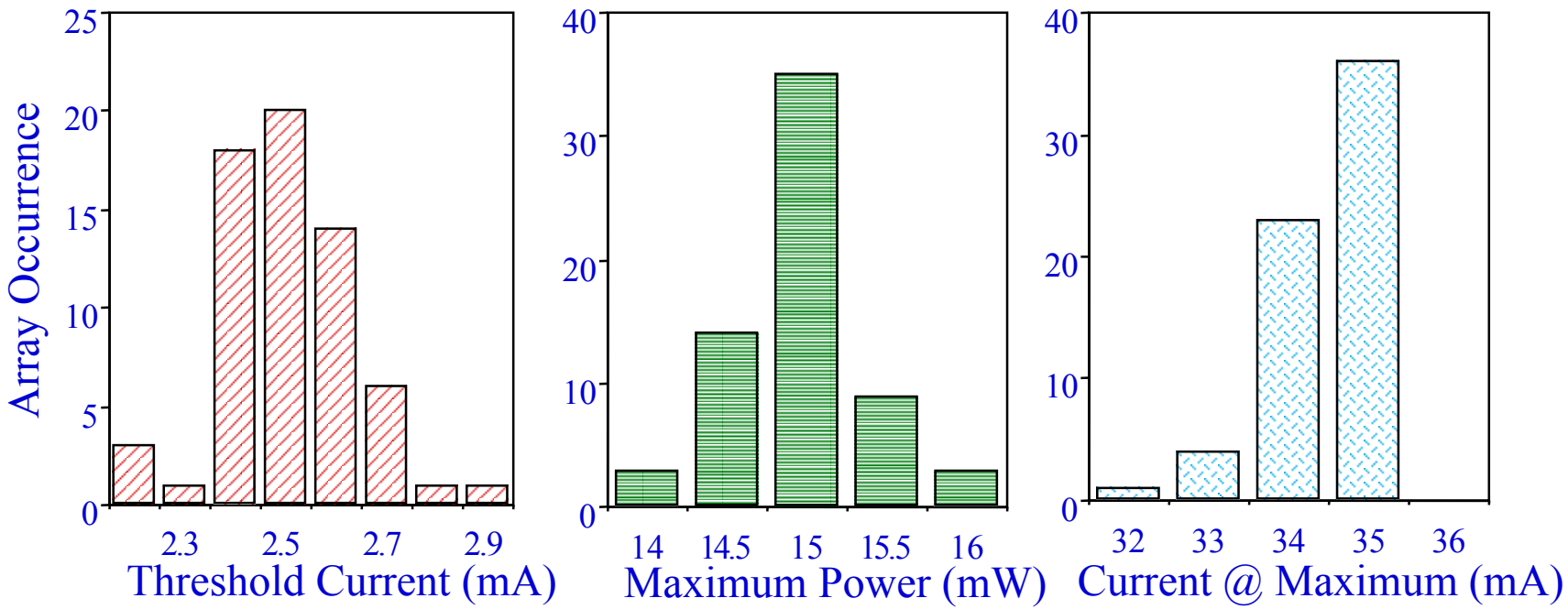
Individually Addressable VCSEL Arrays



8x8 Array
250 μm period
Selective Oxidation
Air-bridge Interconnects

- **2-D array allows for spatial multiplexing of data**
  - A contrast to WDM and TDM
  - Optical channel must maintain spatial integrity
- **64 x 1-Gbps VCSELs gives an aggregate data rate of 64 Gbps.**

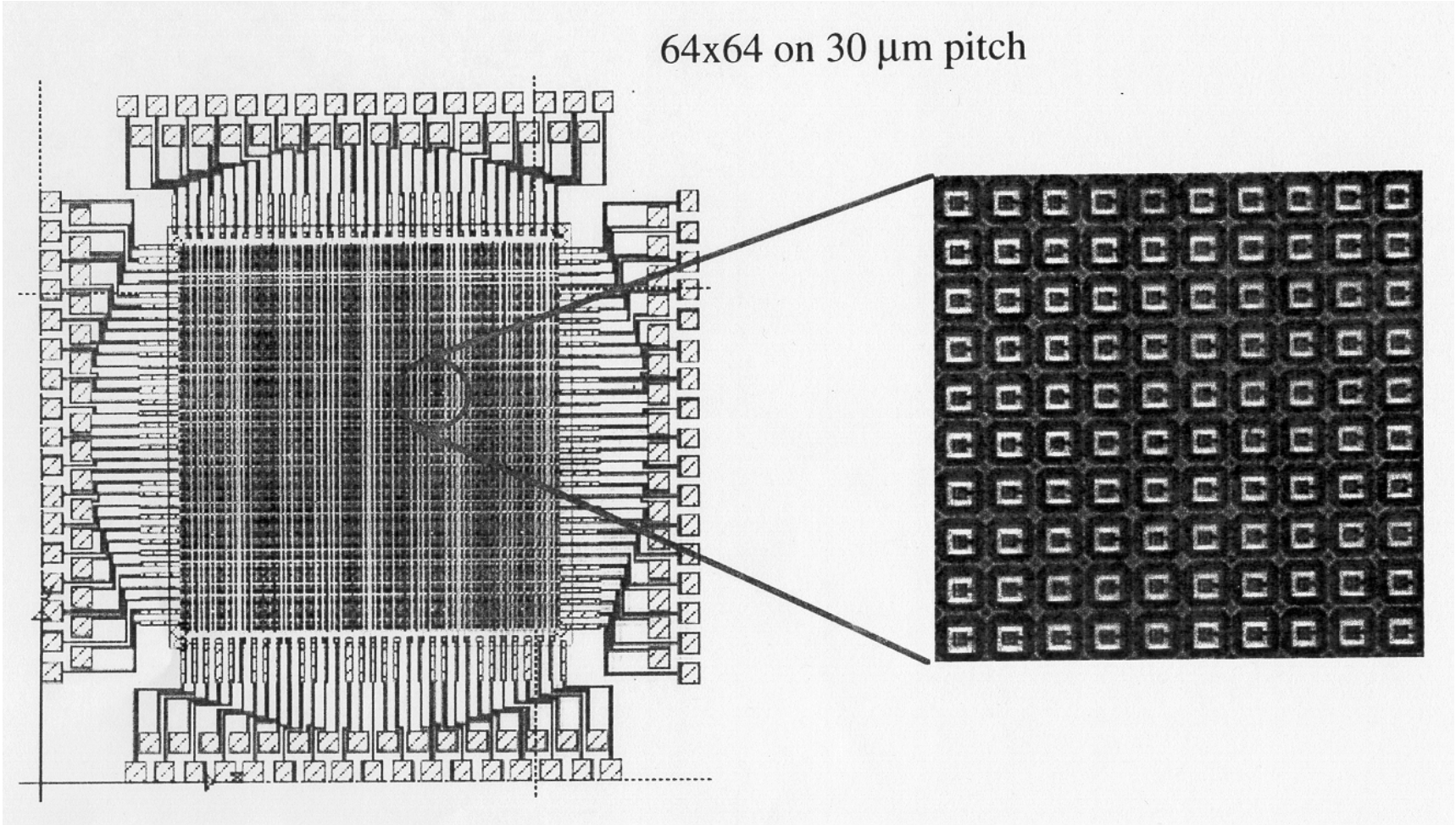
Uniformity of an 8x8 Selectively-Oxidized 850 nm VCSEL Array



- **Threshold current: 2.5±0.1 mA (±5%)**
- **Maximum power: 15.2±0.4 mW (±2.8%)**
- **Operating current : 34.3±0.6 mA (±1.8%)**

- **Lower power arrays have similar uniformity performance.**

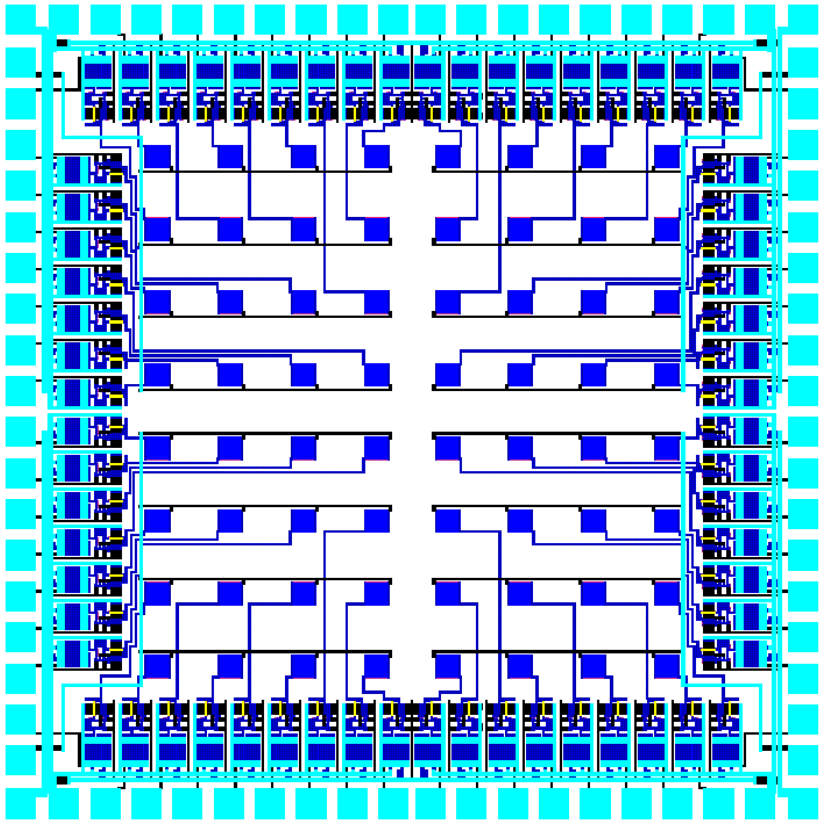
Matrix Addressable 2D Oxidized VCSEL Arrays for Imaging, Display and Interconnect Applications



SNL has demonstrated 128X128=16.4K arrays

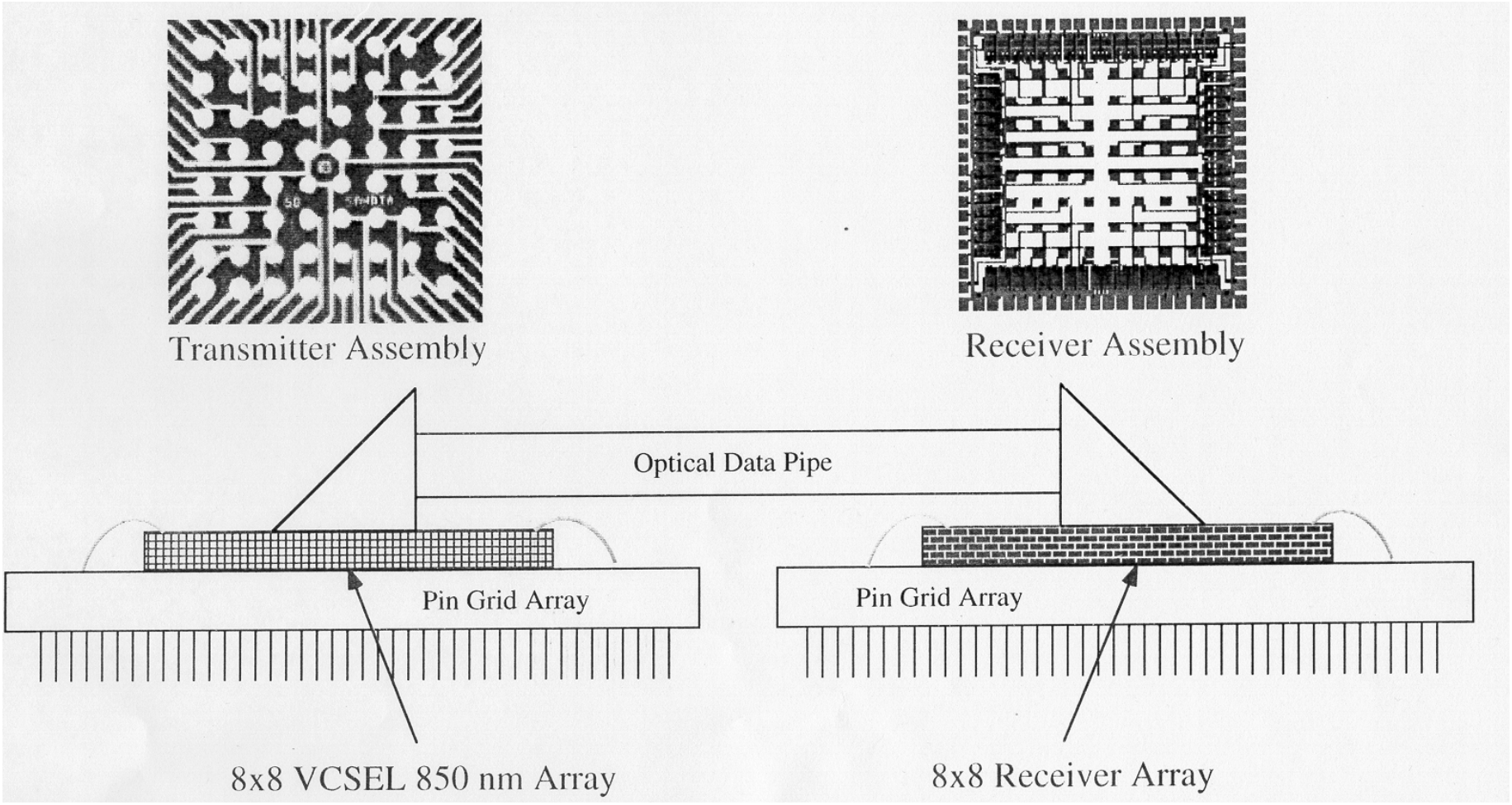
Photoreceiver Array

with Joy Laskar, and Carl Chun, Georgia Institute of Technology

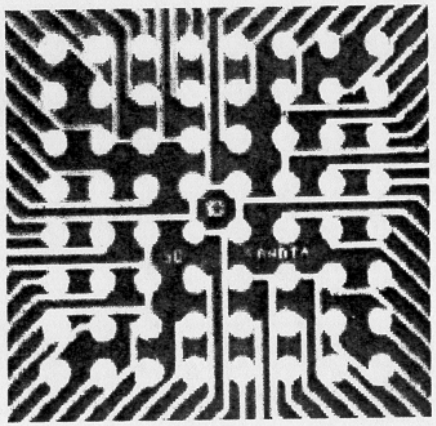


- 100Mbps receiver front end with CMOS compatible output
- MSM photdetectors on 250μm pitch provide input to amplifiers
- Pads at periphery for extraction of the output signal
- 1Gbps Triquint Process

A High Density Optical Interconnect Approach



An Integrated Microsystem Approach



2-D VCSEL Arrays
Ultralow I_{th}, V_{th}
Low input power

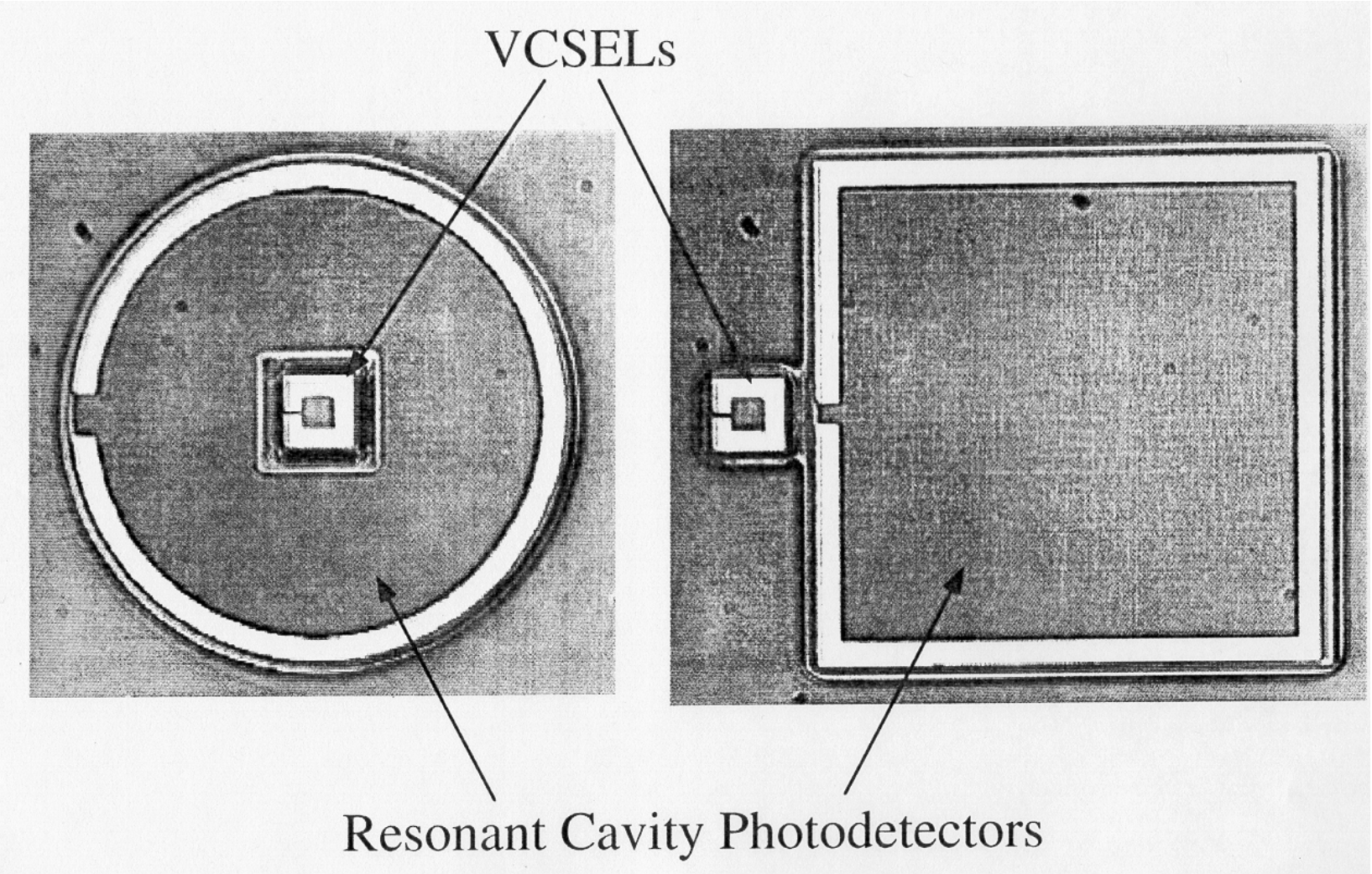
Integrated Photodetectors
Resonant Cavity, MSM, PIN
Intermeshed w/ VCSELs

Collimating Lenses
Focusing Lenses
Polarizers

Si/GaAs Electronic Circuits:
Driving, Amplifying, Logic

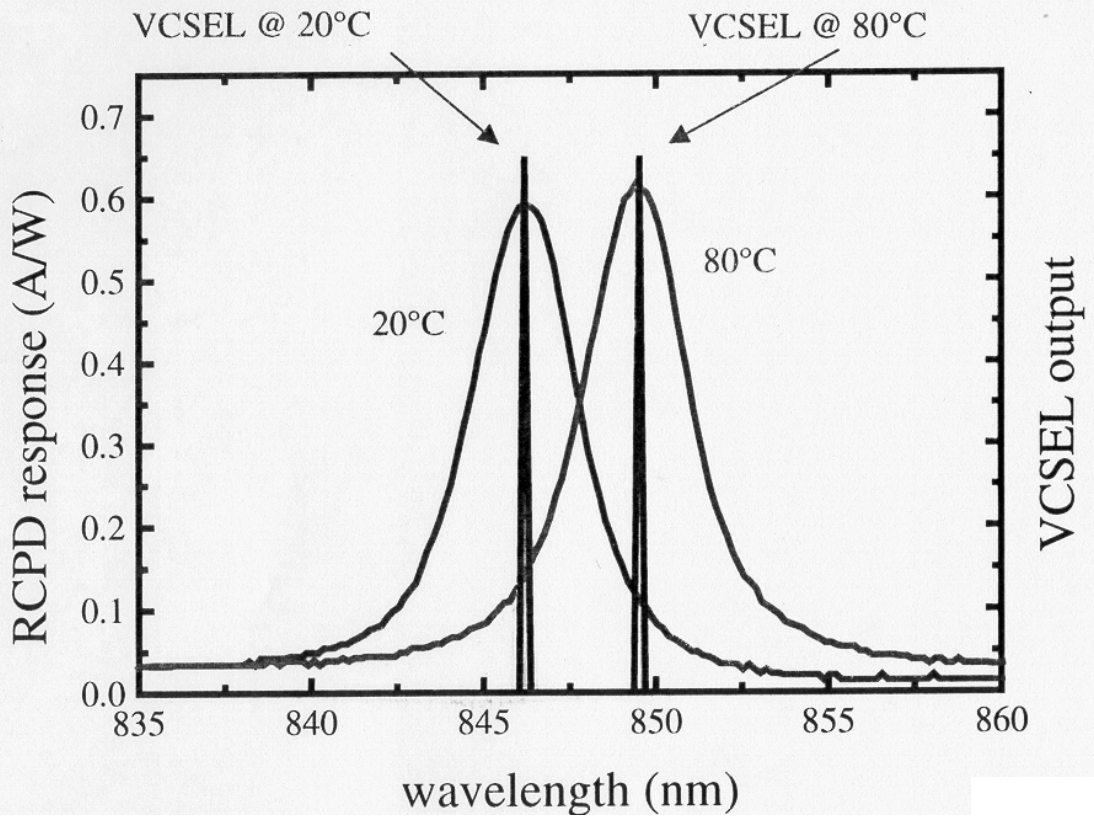
Integration Technologies:
Flip-Chip Bonding
Thin Film Integration
Wafer Fusion
Monolithic

Monolithically Integrated VCSEL-RCPDs



VCSEL-RCPD Spectral Tracking

- Both the VCSEL and RCPD share the same cavity resonance.
- Both the VCSEL and RCPD shift at ~0.06nm/°C.



Radiation-Hard (Al,Ga)As Photodetectors at Sandia

	Responsivity	Bandwidth	Dark Current	Bias
	(A/W)	(GHz)	(pA)	(V)
MSM	0.42	>7	<100	>1
pin	0.62	(>10)	<10	>1
RCPD	0.28	(>1)	<10	>1
HPT	>20	1.10	<100	>1