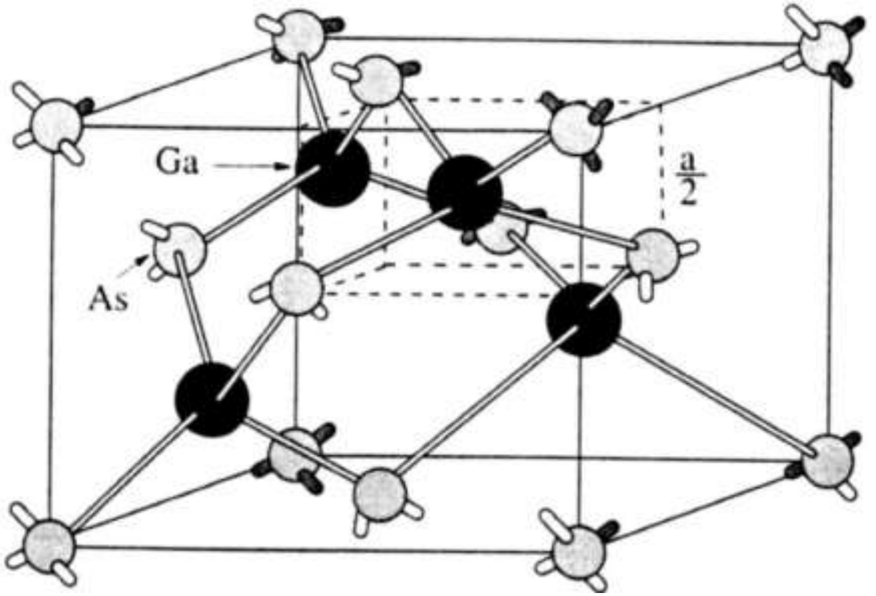
The Impact of Strained Quantum Well Lasers

J. J. Coleman
University of Illinois

Photons, Electrons, Bands: A Symposium on the Diversity of Opto-Electronics

Pre-Lunch Quiz (answers later)

Strained Layers - Simple Elegant Concept



GaAs - zincblende lattice

Despite the apparent complexity, this is a *symmetric* structure.

What happens if you make it asymmetric?

Can you distort the unit cell? How? What happens?

Strain Accommodation

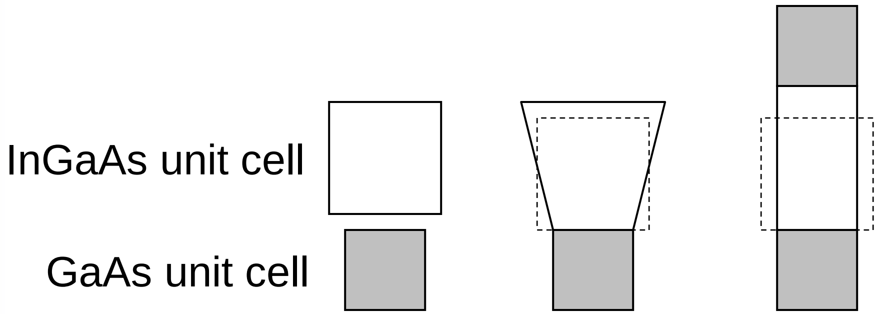
Semiconductors are not completely inflexible

– they have some (small) amount of elasticity

InGaAs

the unit cell of InGaAs can be as much as 3.6% larger (at x=0.50) than GaAs

in layered structures, this leads to *tetragonal distortion*



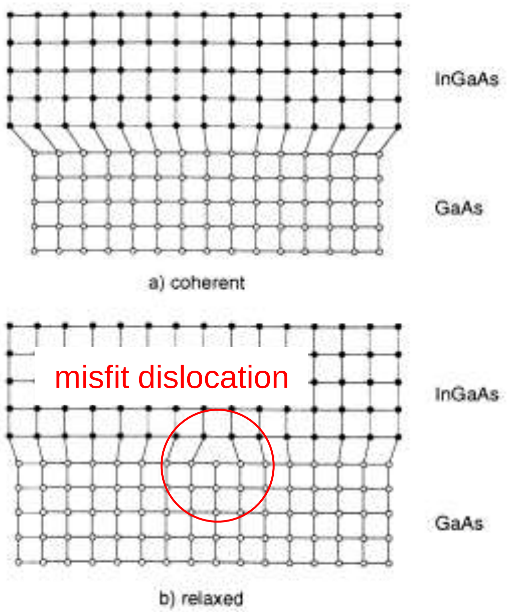
atoms are compressed in the plane (biaxial compression) and elongate normal to the plane (uniaxial tension) while the volume remains about the same

Strain Accommodation

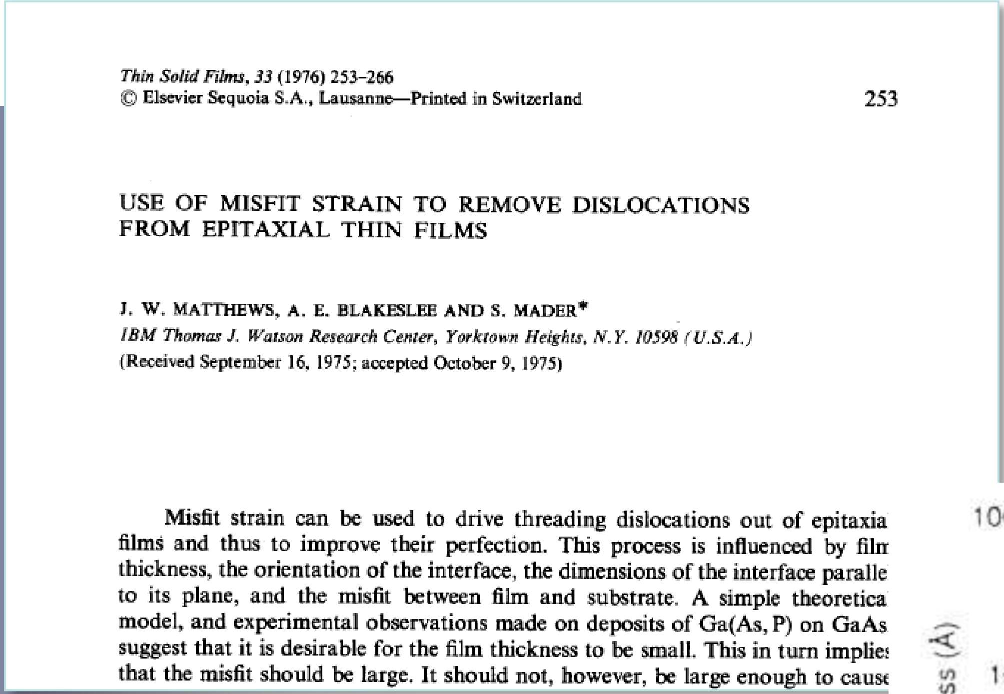
- if a layer is thin enough, even though it is mismatched from the host lattice constant, the strain can be accommodated elastically - without the formation of dislocations.
- the maximum layer thickness for elastic strain accommodation is the *critical thickness* h_c

coherent – strain is accommodated elastically

relaxed – strain accommodated by dislocations



Matthews and Blakeslee Model



Thin Solid Films, 33 (1976) 253–266
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USE OF MISFIT STRAIN TO REMOVE DISLOCATIONS
FROM EPITAXIAL THIN FILMS

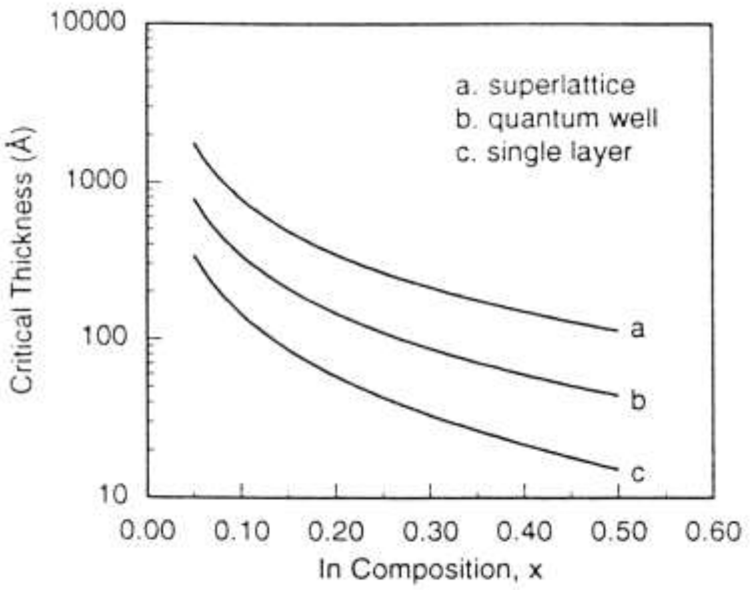
J. W. MATTHEWS, A. E. BLAKESLEE AND S. MADER*
IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. 10598 (U.S.A.)

(Received September 16, 1975; accepted October 9, 1975)

Misfit strain can be used to drive threading dislocations out of epitaxia films and thus to improve their perfection. This process is influenced by film thickness, the orientation of the interface, the dimensions of the interface paralle to its plane, and the misfit between film and substrate. A simple theoretica model, and experimental observations made on deposits of Ga(As, P) on GaAs suggest that it is desirable for the film thickness to be small. This in turn implie that the misfit should be large. It should not, however, be large enough to cause

balancing forces gives an expression for the critical thickness

$$h_c = \frac{a}{k\sqrt{2\pi\varepsilon}}\,\frac{1-0.25\upsilon}{1+\upsilon}\left(\ln\frac{h_c\sqrt{2}}{a}+1\right)$$

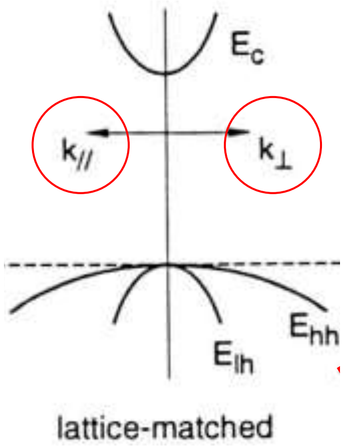


Strain Effects on Energy Bands

two effective directions

in-plane (//)

perpendicular to the plane (⊥)

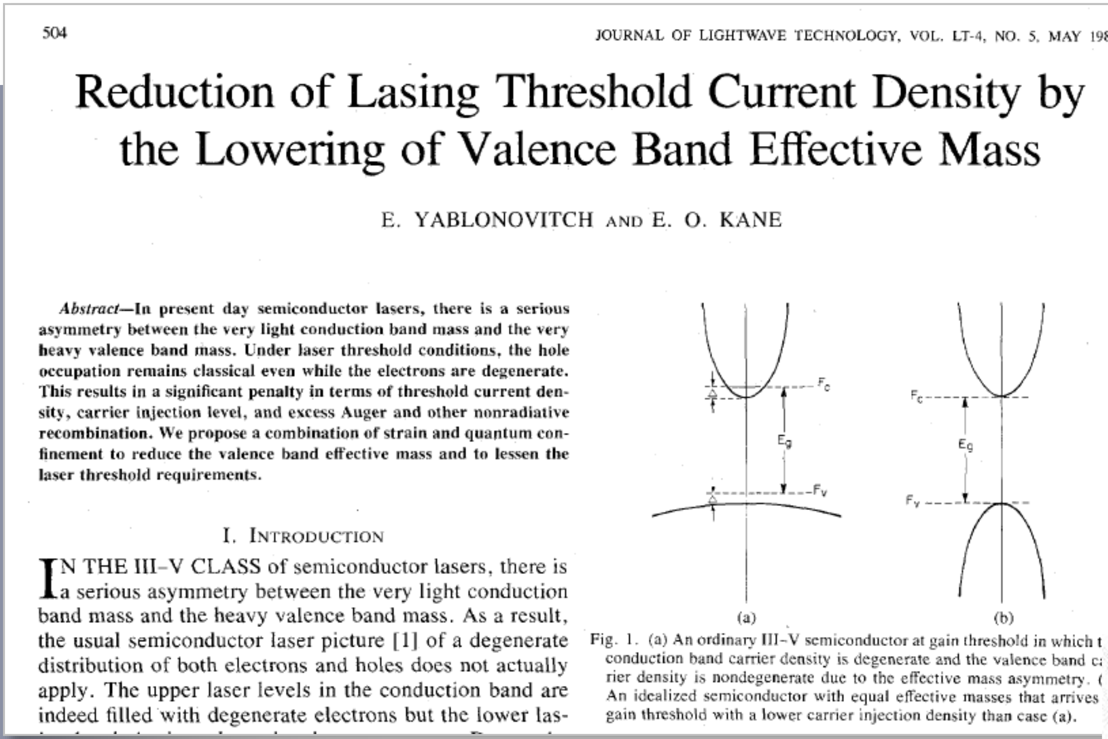


strain has a pronounced effect on the valence band structure of III-V materials

- it removes the degeneracy in the valence band (shifting the band edge energies)
- it also removes the symmetry (resulting in different effective masses in different directions)

ILLINOIS

Possibilities



504 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. LT-4, NO. 5, MAY 1986

Reduction of Lasing Threshold Current Density by the Lowering of Valence Band Effective Mass

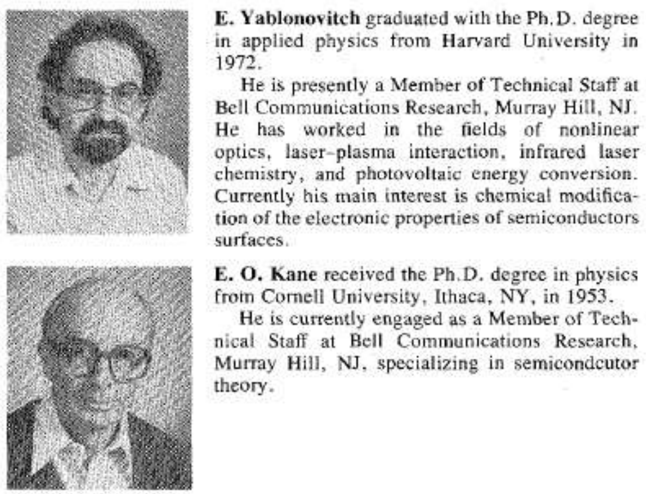
E. YABLONOVITCH AND E. O. KANE

Abstract—**In present day semiconductor lasers, there is a serious asymmetry between the very light conduction band mass and the very heavy valence band mass. Under laser threshold conditions, the hole occupation remains classical even while the electrons are degenerate. This results in a significant penalty in terms of threshold current density, carrier injection level, and excess Auger and other nonradiative recombination. We propose a combination of strain and quantum confinement to reduce the valence band effective mass and to lessen the laser threshold requirements.**

I. INTRODUCTION

IN THE III–V CLASS of semiconductor lasers, there is a serious asymmetry between the very light conduction band mass and the heavy valence band mass. As a result, the usual semiconductor laser picture [1] of a degenerate distribution of both electrons and holes does not actually apply. The upper laser levels in the conduction band are indeed filled with degenerate electrons but the lower las-

Fig. 1. (a) An ordinary III–V semiconductor at gain threshold in which t conduction band carrier density is degenerate and the valence band c rier density is nondegenerate due to the effective mass asymmetry. (An idealized semiconductor with equal effective masses that arrives gain threshold with a lower carrier injection density than case (a).



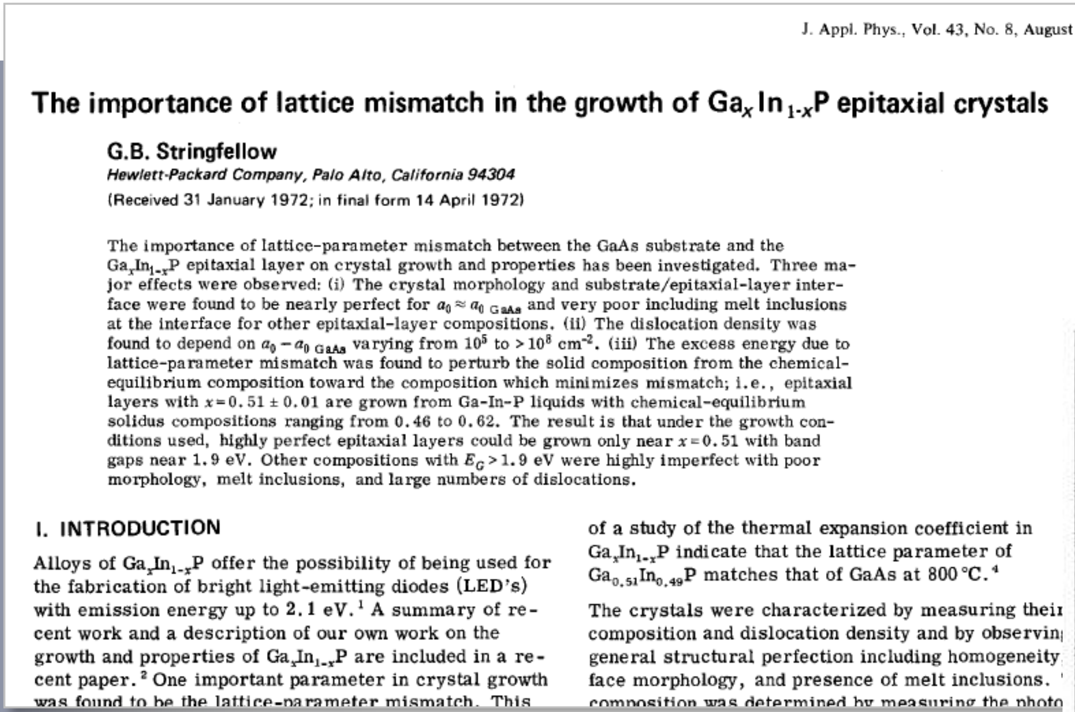
E. Yablonovitch graduated with the Ph.D. degree in applied physics from Harvard University in 1972.

He is presently a Member of Technical Staff at Bell Communications Research, Murray Hill, NJ. He has worked in the fields of nonlinear optics, laser–plasma interaction, infrared laser chemistry, and photovoltaic energy conversion. Currently his main interest is chemical modification of the electronic properties of semiconductors surfaces.

E. O. Kane received the Ph.D. degree in physics from Cornell University, Ithaca, NY, in 1953.

He is currently engaged as a Member of Technical Staff at Bell Communications Research, Murray Hill, NJ, specializing in semicondcutor theory.

Conventional Wisdom



J. Appl. Phys., Vol. 43, No. 8, August 1972

The importance of lattice mismatch in the growth of $Ga_xIn_{1-x}P$ epitaxial crystals

G.B. Stringfellow
Hewlett-Packard Company, Palo Alto, California 94304

(Received 31 January 1972; in final form 14 April 1972)

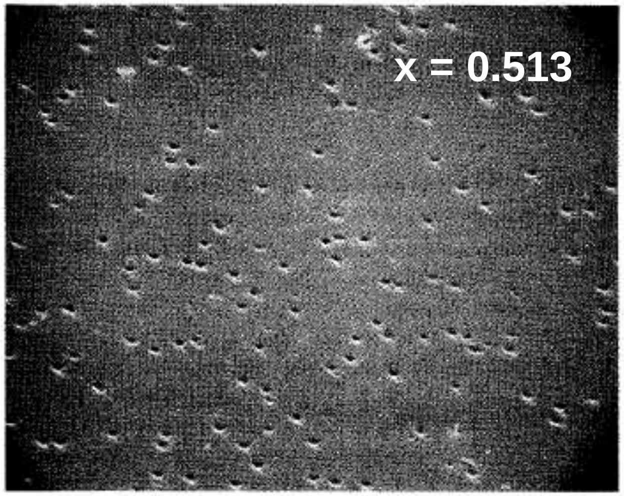
The importance of lattice-parameter mismatch between the GaAs substrate and the $Ga_xIn_{1-x}P$ epitaxial layer on crystal growth and properties has been investigated. Three major effects were observed: (i) The crystal morphology and substrate/epitaxial-layer interface were found to be nearly perfect for $a_0 \approx a_{0\ \mathrm{GaAs}}$ and very poor including melt inclusions at the interface for other epitaxial-layer compositions. (ii) The dislocation density was found to depend on $a_0 - a_{0\ \mathrm{GaAs}}$ varying from 10^5 to $>10^8$ cm^{-2}. (iii) The excess energy due to lattice-parameter mismatch was found to perturb the solid composition from the chemical-equilibrium composition toward the composition which minimizes mismatch; i.e., epitaxial layers with $x = 0.51 \pm 0.01$ are grown from Ga-In-P liquids with chemical-equilibrium solidus compositions ranging from 0.46 to 0.62. The result is that under the growth conditions used, highly perfect epitaxial layers could be grown only near $x = 0.51$ with band gaps near 1.9 eV. Other compositions with $E_G > 1.9$ eV were highly imperfect with poor morphology, melt inclusions, and large numbers of dislocations.

I. INTRODUCTION

Alloys of $Ga_xIn_{1-x}P$ offer the possibility of being used for the fabrication of bright light-emitting diodes (LED's) with emission energy up to 2.1 eV.[1] A summary of recent work and a description of our own work on the growth and properties of $Ga_xIn_{1-x}P$ are included in a recent paper.[2] One important parameter in crystal growth was found to be the lattice-parameter mismatch. This

of a study of the thermal expansion coefficient in $Ga_xIn_{1-x}P$ indicate that the lattice parameter of $Ga_{0.51}In_{0.49}P$ matches that of GaAs at 800 °C.[4]

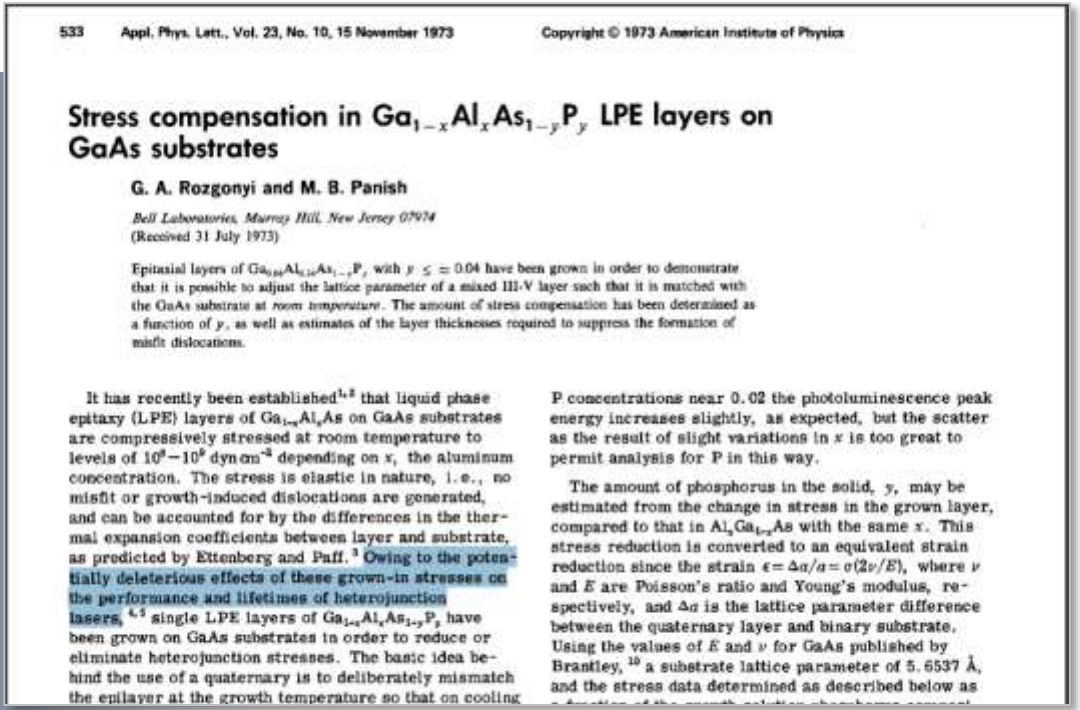
The crystals were characterized by measuring thei composition and dislocation density and by observin general structural perfection including homogeneity face morphology, and presence of melt inclusions. composition was determined by measuring the photo



x = 0.513

"The morphology, homogeneity, and structural perfection break down for alloys with $|x_{epi} - 0.51| > 0.01$."

Conventional Wisdom



533 Appl. Phys. Lett., Vol. 23, No. 10, 15 November 1973

Stress compensation in $Ga_{1-x}Al_xAs_{1-y}P_y$ LPE layers on GaAs substrates

G. A. Rozgonyi and M. B. Panish

Bell Laboratories, Murray Hill, New Jersey 07974

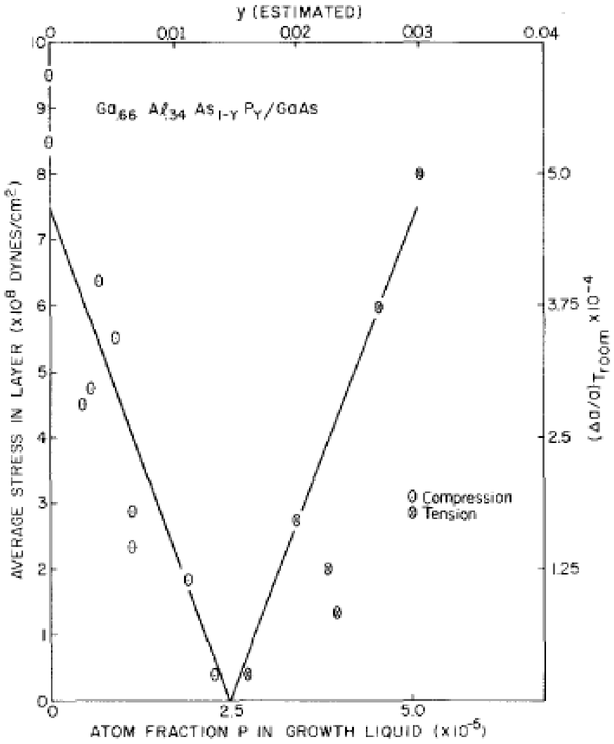
(Received 31 July 1973)

Epitaxial layers of $Ga_{0.66}Al_{0.34}As_{1-y}P_y$ with $y \leq \simeq 0.04$ have been grown in order to demonstrate that it is possible to adjust the lattice parameter of a mixed III-V layer such that it is matched with the GaAs substrate at *room temperature*. The amount of stress compensation has been determined as a function of y, as well as estimates of the layer thicknesses required to suppress the formation of misfit dislocations.

It has recently been established[1,2] that liquid phase epitaxy (LPE) layers of $Ga_{1-x}Al_xAs$ on GaAs substrates are compressively stressed at room temperature to levels of 10^8-10^9 dyn cm^{-2} depending on x, the aluminum concentration. The stress is elastic in nature, i.e., no misfit or growth-induced dislocations are generated, and can be accounted for by the differences in the thermal expansion coefficients between layer and substrate, as predicted by Ettenberg and Paff.[3] Owing to the potentially deleterious effects of these grown-in stresses on the performance and lifetimes of heterojunction lasers,[4,5] single LPE layers of $Ga_{1-x}Al_xAs_{1-y}P_y$ have been grown on GaAs substrates in order to reduce or eliminate heterojunction stresses. The basic idea behind the use of a quaternary is to deliberately mismatch the epilayer at the growth temperature so that on cooling

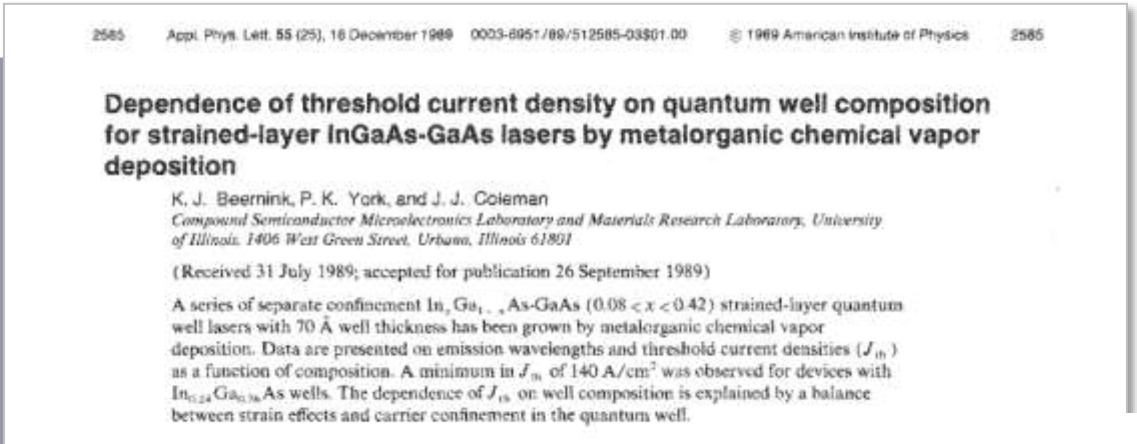
P concentrations near 0.02 the photoluminescence peak energy increases slightly, as expected, but the scatter as the result of slight variations in x is too great to permit analysis for P in this way.

The amount of phosphorus in the solid, y, may be estimated from the change in stress in the grown layer, compared to that in $Al_xGa_{1-x}As$ with the same x. This stress reduction is converted to an equivalent strain reduction since the strain $\epsilon = \Delta a/a = \sigma(2\nu/E)$, where ν and E are Poisson's ratio and Young's modulus, respectively, and Δa is the lattice parameter difference between the quaternary layer and binary substrate. Using the values of E and ν for GaAs published by Brantley,[10] a substrate lattice parameter of 5.6537 Å, and the stress data determined as described below as



“Owing to the potentially deleterious effects of these grown-in stresses on the performance and lifetimes of heterojunction lasers….”

Experimental Work at Illinois



2585 Appl. Phys. Lett. 55 (25), 18 December 1989 0003-6951/89/512585-03$01.00 © 1989 American Institute of Physics 2585

Dependence of threshold current density on quantum well composition for strained-layer InGaAs-GaAs lasers by metalorganic chemical vapor deposition

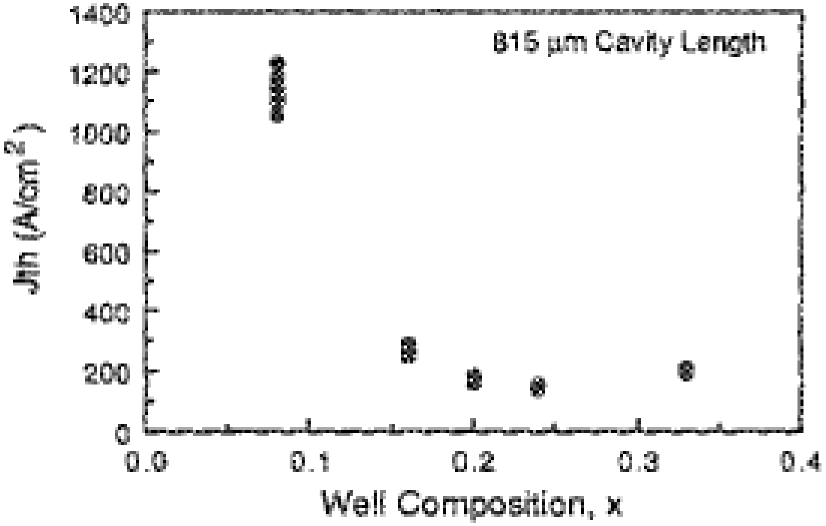
K. J. Beernink, P. K. York, and J. J. Coleman
Compound Semiconductor Microelectronics Laboratory and Materials Research Laboratory, University of Illinois, 1406 West Green Street, Urbana, Illinois 61801

(Received 31 July 1989; accepted for publication 26 September 1989)

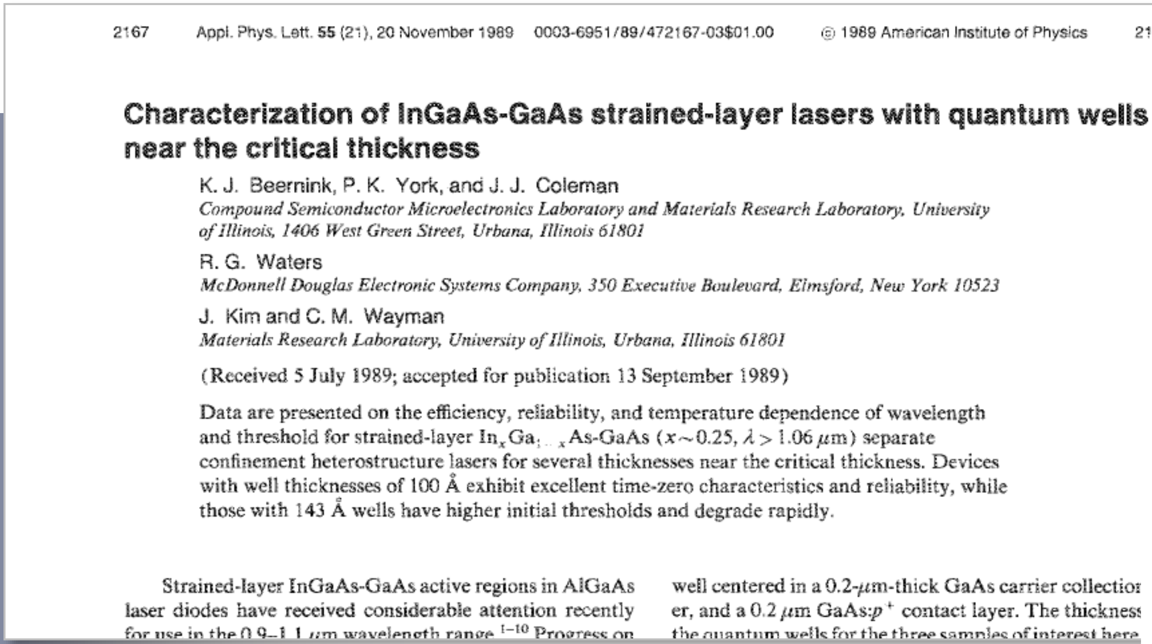
A series of separate confinement $In_xGa_{1-x}As$-GaAs ($0.08 < x < 0.42$) strained-layer quantum well lasers with 70 Å well thickness has been grown by metalorganic chemical vapor deposition. Data are presented on emission wavelengths and threshold current densities (J_{th}) as a function of composition. A minimum in J_{th} of 140 A/cm^2 was observed for devices with $In_{0.24}Ga_{0.76}As$ wells. The dependence of J_{th} on well composition is explained by a balance between strain effects and carrier confinement in the quantum well.

The use of lattice-mismatched thin layer structures in which the strain is accommodated elastically allows for greater flexibility in the design of semiconductor devices.

oxide-defined stripes
lapped and polished to
and *n*-type contacts w



Experimental Results - Reliability



2167 Appl. Phys. Lett. **55** (21), 20 November 1989 0003-6951/89/472167-03$01.00 © 1989 American Institute of Physics 2167

Characterization of InGaAs-GaAs strained-layer lasers with quantum wells near the critical thickness

K. J. Beernink, P. K. York, and J. J. Coleman
Compound Semiconductor Microelectronics Laboratory and Materials Research Laboratory, University of Illinois, 1406 West Green Street, Urbana, Illinois 61801
R. G. Waters
McDonnell Douglas Electronic Systems Company, 350 Executive Boulevard, Elmsford, New York 10523
J. Kim and C. M. Wayman
Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801

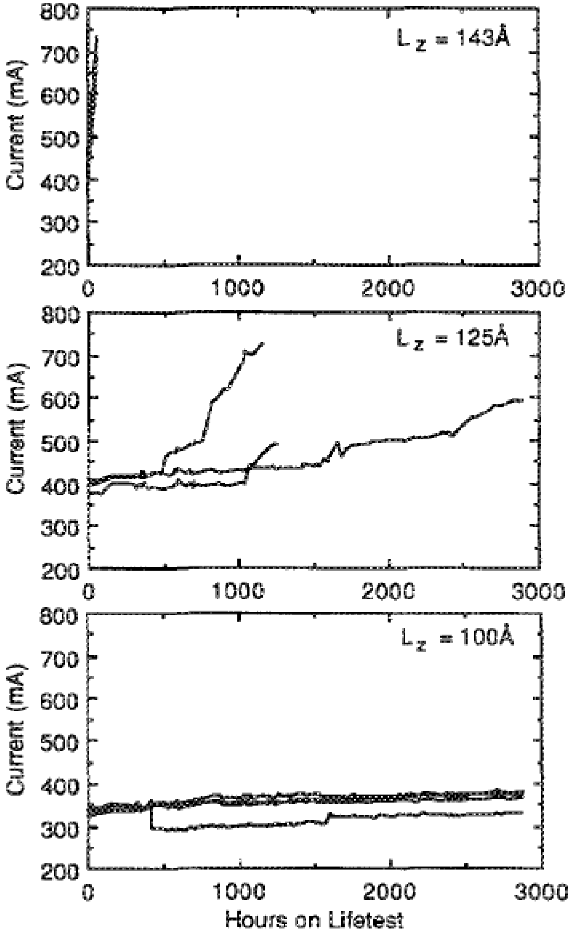
(Received 5 July 1989; accepted for publication 13 September 1989)

Data are presented on the efficiency, reliability, and temperature dependence of wavelength and threshold for strained-layer $In_xGa_{1-x}As$-GaAs ($x \sim 0.25$, $\lambda > 1.06$ μm) separate confinement heterostructure lasers for several thicknesses near the critical thickness. Devices with well thicknesses of 100 Å exhibit excellent time-zero characteristics and reliability, while those with 143 Å wells have higher initial thresholds and degrade rapidly.

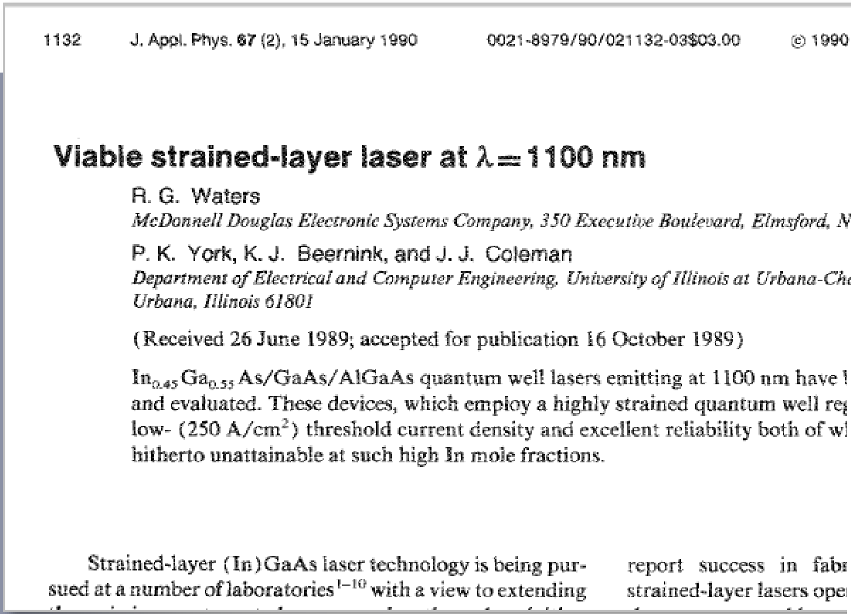
Strained-layer InGaAs-GaAs active regions in AlGaAs laser diodes have received considerable attention recently for use in the 0.9–1.1 μm wavelength range.[1–10] Progress on

well centered in a 0.2-μm-thick GaAs carrier collectio er, and a 0.2 μm GaAs:p^+ contact layer. The thickness the quantum wells for the three samples of interest here

MCDONNELL DOUGLAS



Experimental Results - Reliability



1132 J. Appl. Phys. 67 (2), 15 January 1990 0021-8979/90/021132-03$03.00 © 1990 American Institute of Physics 1132

Viable strained-layer laser at λ=1100 nm

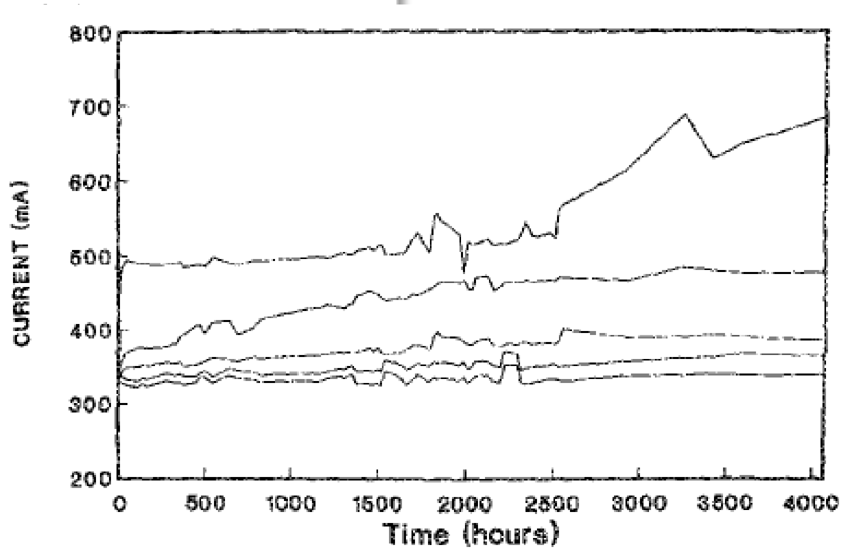
R. G. Waters
McDonnell Douglas Electronic Systems Company, 350 Executive Boulevard, Elmsford, New York 10523
P. K. York, K. J. Beernink, and J. J. Coleman
Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 26 June 1989; accepted for publication 16 October 1989)

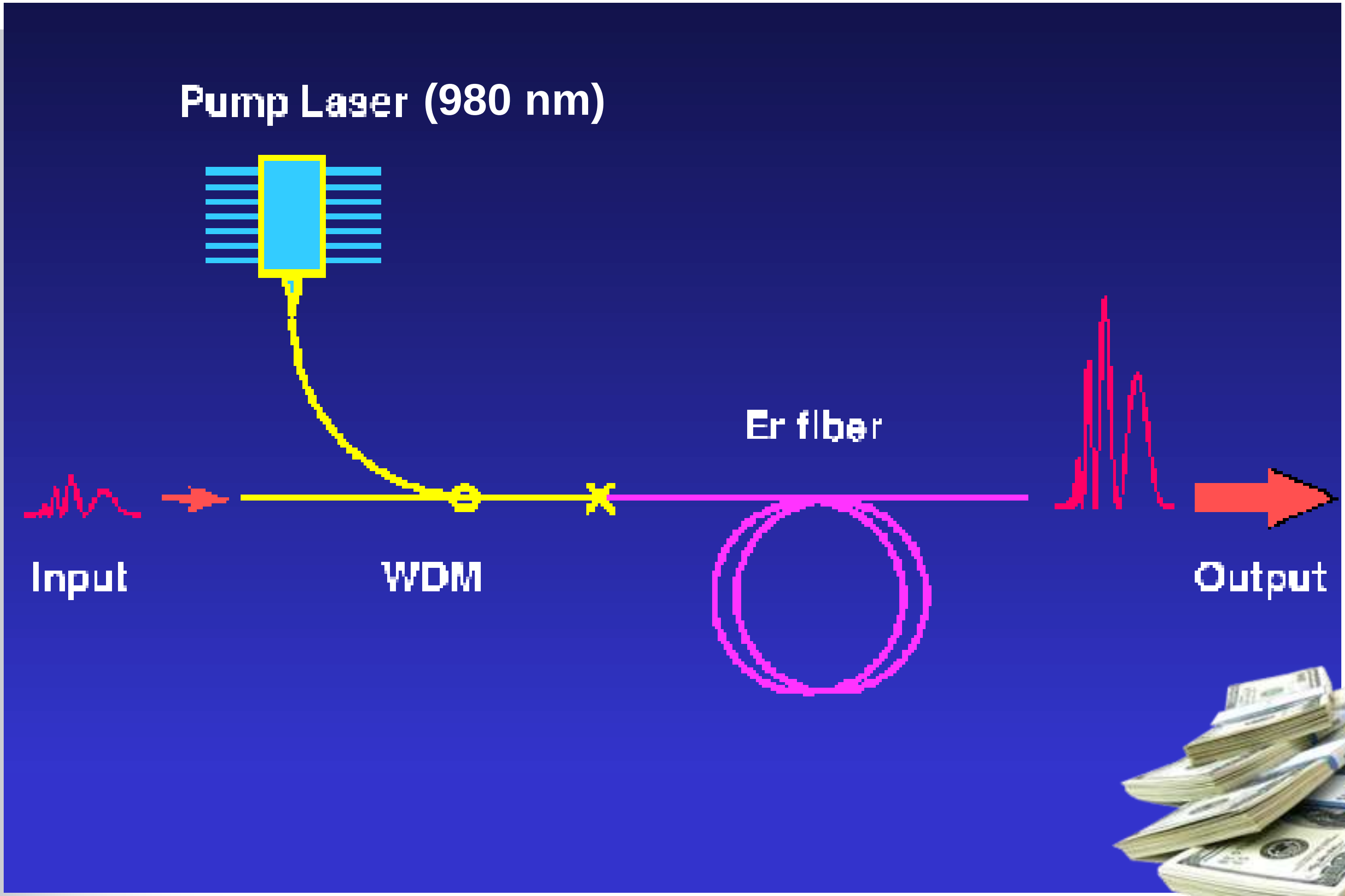
$In_{0.45}Ga_{0.55}As/GaAs/AlGaAs$ quantum well lasers emitting at 1100 nm have
and evaluated. These devices, which employ a highly strained quantum well re
low- (250 A/cm^2) threshold current density and excellent reliability both of w
hitherto unattainable at such high In mole fractions.

Strained-layer (In)GaAs laser technology is being pursued at a number of laboratories[1–10] with a view to extending

report success in fab
strained-layer lasers ope



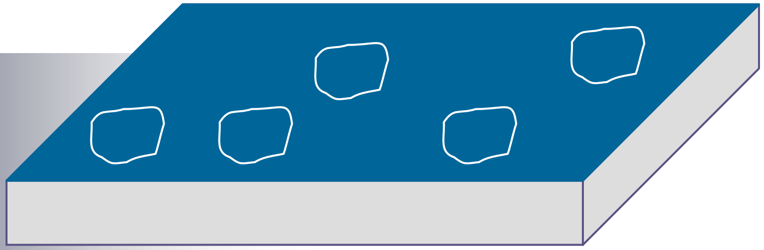
Killer Ap - EDFA



Implications of Strained Layer Lasers?

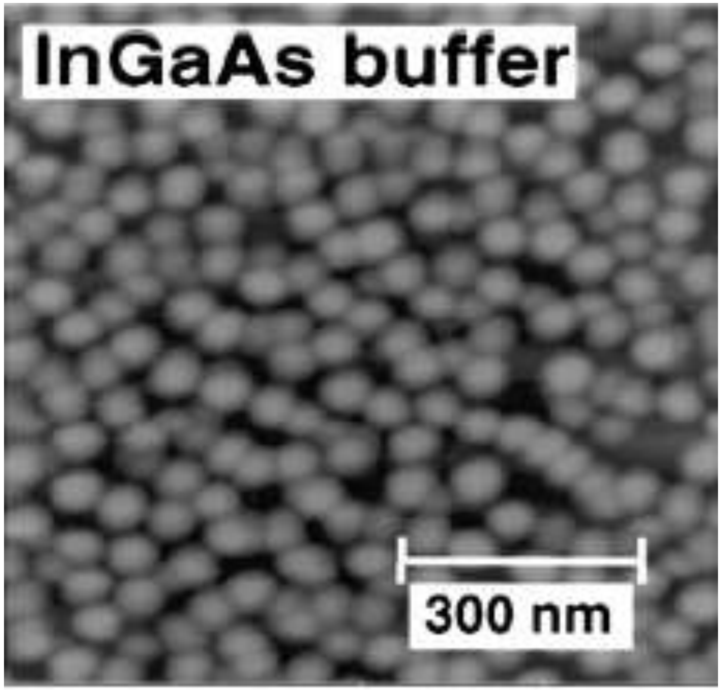
- Strain engineering
- Intentional lattice mismatch as a design tool
- Important new wavelength ranges (i.e. 900-1100 nm)
- Acceptable reliability became *enhanced* reliability with In-incorporation
- The EDFA became a critical component in lightwave systems
- High reliability Al-free lasers
- Strain-compensated device designs
- Quantum dots*

Quantum Dots



layer to island growth
“wetting layer”

InGaAs dots on GaAs



Huffaker, et. al., JSTQE, 2000

Quiz Answers

Dr. Evan O. Kane

Dave Matthews Band

$7B EDFA market (in 2004 alone)

Gen Thomas L. Kane

thank you

and Happy Birthday, Eli