Extending dot-dash advantages to InP

Mike Cooke reports on recent quantum dot/dash laser diode developments aiming at 1.55μm wavelengths.

Fiber-optic communications depends on an interlocking series of advantages/disadvantages in various structures. For example, while C-band communications at about 1.55μm has the least attenuation in the basic fiber, the E band at 1.3μm has the least dispersion.

In the transmitter section also there are trade-offs between the uses of various systems — light-emitting diodes (LEDs), laser diodes (LDs) — and their material bases: gallium arsenide phosphide (GaAsP) on GaAs substrates and gallium indium arsenide phosphide (GaInAsP) on InP substrates. The GaAsP/GaAs option covers the 1.3μm applications, while GaInAsP/InP is needed for 1.55μm communications.

Qdots/dashes

For InP LDs, much of the present research is focused on using quantum dot (Qdot) or quantum dash (Qdash) structures. Qdot lasers are expected to enable high-speed modulation, low threshold current, and high characteristic temperature (allowing higher-temperature operation). Some success in these respects has been achieved in producing InAs dots on GaAs substrates that lase in the 0.9–1.4μm range.

For 1.55μm, the InAs/InP system is seen as being more suitable in terms of the resulting dot sizes due to the lower lattice mismatch between the materials (3.2%) compared with GaAs-based dots (7.2%). Unfortunately, rather than forming round dots of suitable size (~25nm diameter), a high density of wires/dashes extended in the $[1\bar{1}0]$ lattice direction or too large (50nm diameter) dots tend to result, depending on the growth conditions.

There are a number of approaches that are being researched for use of the InAs/InP system as a Qdot-like system. One is to find ways to reduce the dash-like character of the confinement structures by using special growth techniques or substrates. Another is to live with and grow to love the peculiar characteristics of dashes. A further approach is to abandon the self-assembly normally used to create dots/dashes and build controlled, specially shaped structures directly using photolithography techniques.

Reorientation

One technique that reduces dot sizes is to use InP substrates oriented in the high-index (113)B plane direction rather than the more usual low-index (001).

Researchers based in France at the Institut National des Sciences Appliquées (INSA) de Rennes have been investigating the optimal substrate orientation for creating InAs Qdots on InP substrates for 1.55μm communication laser wavelengths [1]. With (113)B substrates, INSA achieved smaller dots (of about 25nm diameter) and low threshold currents in laser diodes produced using the dots. However, such substrates are difficult to incorporate into standard InP production technology.

Another approach being explored at INSA in France is to use substrates that are cut off the (001) InP crystal ingot with a somewhat misoriented surface that reduces the tendency to form wires, dashes or larger dots. The investigation involved comparing the structures produced with misorientations of about 2º in the (111)A or (111)B directions, and a nominal on-axis (001) sample.

A Riber 32 gas-source molecular-beam epitaxy (GSMBE) system was used to create the Qdot structures. It was found that the arsenic flux is also critical for producing suitable Qdots. The buffer layer on which the dots were grown was $Ga_{0.2}In_{0.8}As_{0.435}P_{0.565}$, which is lattice matched to the InP substrate. The emission wavelength of the buffer layer is 1.18μm.

A high flow of 6 standard cubic centimeters (sccm) of the arsine (AsH_3) source gas (resulting in an As flux of about 30x the In flux) leads in all cases to large dots (60–65nm base diameter). However, 0.3sccm of AsH_3 results in smaller isotropic dots on the B-surface substrates (Figure 1). The 2nm-high dots measure 30–35nm in diameter and are produced with a density of $7x10^{10}$Qdots/cm^2. The dot height varies by around 30%, irrespective of the arsine flow rate.

The 1nm-high structures grown on nominal and A-surface substrates are elongated in the $[1\bar{1}0]$ direction. The elongations are 200–500nm and 100–200nm for the nominal and A-surface substrates, respectively.

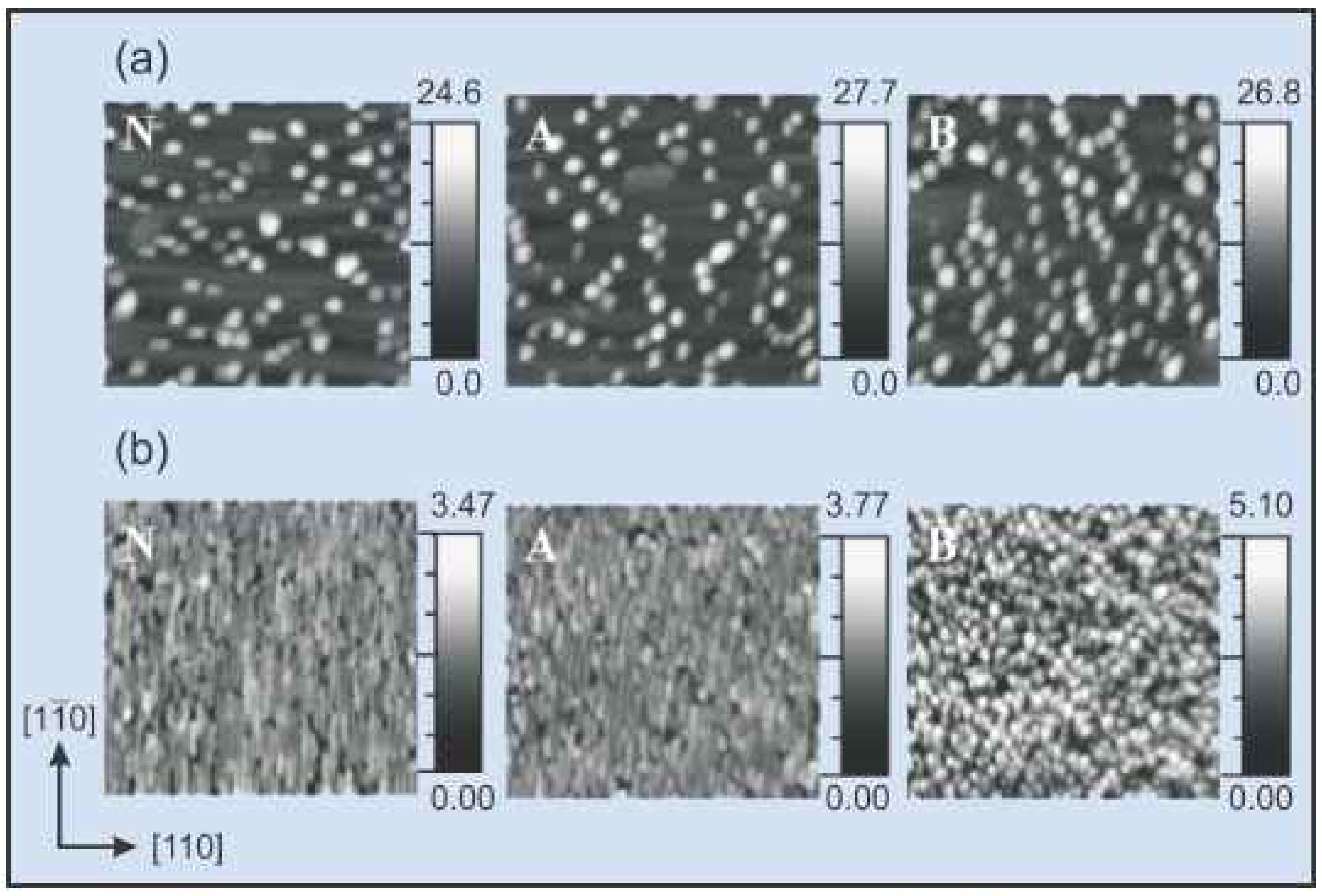

Figure 1. Atomic force microscopy of InAs Qdot/Qdash structures produced at Institut National des Sciences Appliquées (INSA) de Rennes, France, on miscut (001) InP substrates. The arsine flow rate is varied: (a) 6sccm and (b) 0.3sccm. The scan field is 1μm x 1μm. N = nominal on-axis (001) InP surface, A = (001) InP surface miscut in the (111)A direction, B = similar miscutting in the (111)B direction. High densities of smaller dots (rather than large dots or dashes) are only produced on the B-miscut substrate with a lower flow rate.

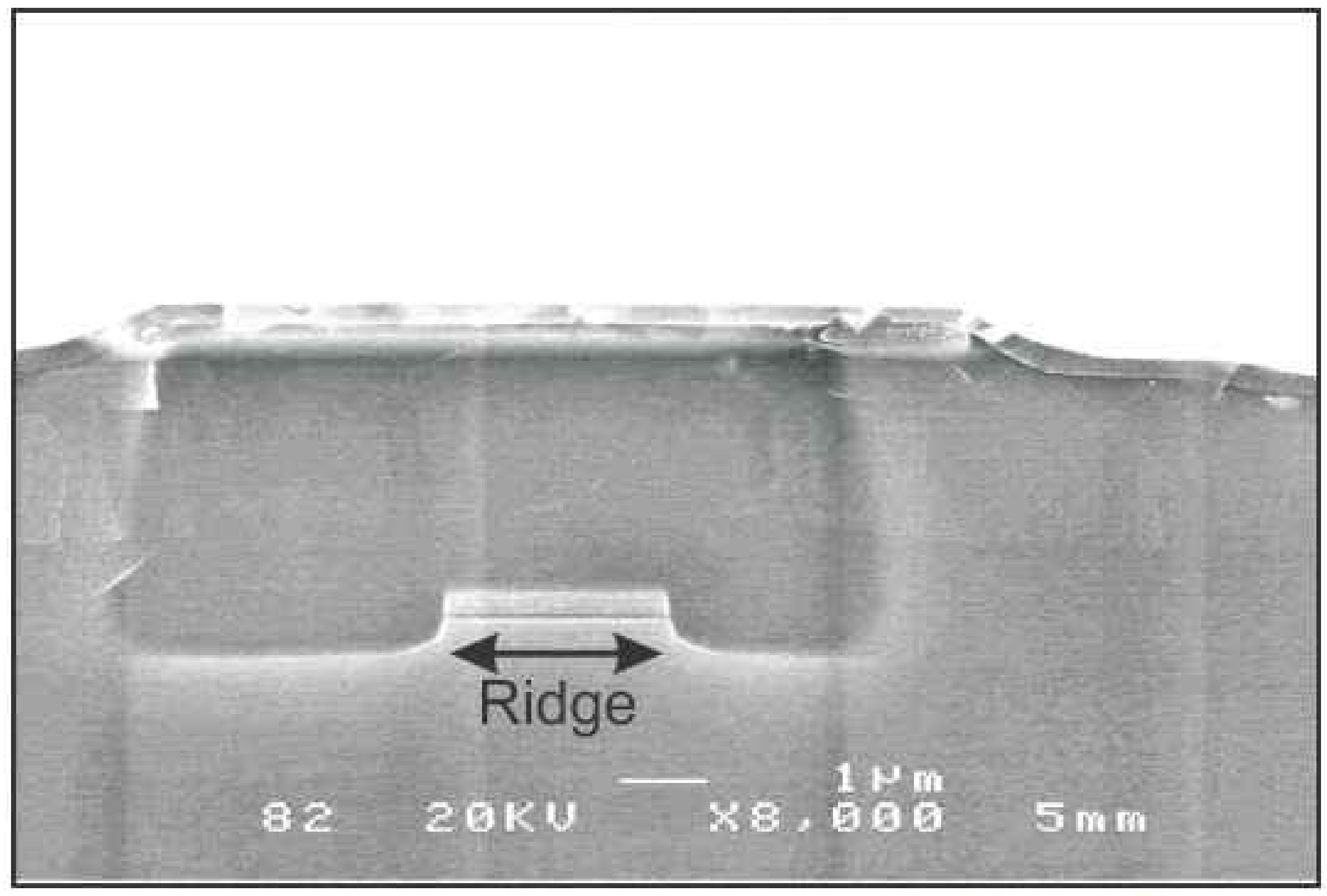

Figure 2. Scanning electron micrograph (SEM) of Alcatel-Thales III-V Labs' buried ridge stripe laser. The ridge measures 2.5μm and contains a stack of six active QDash layers.

Focusing on B-surface substrates, a variation of temperature was then investigated, growing dots at 400°C and 450°C, in addition to the 480°C of the previous experiments with the range of substrates and flow rates. The lower arsine flow rate was naturally used as giving better results at 480°C. A modest increase in dot density to $9x10^{10}$Qdots/cm^2, and a decrease in dimensions to 26nm diameter and 1nm height, was achieved with decreasing temperature.

A double capping process, using the same $Ga_{0.2}In_{0.8}As_{0.435}P_{0.565}$ material composition as in the buffer layer, allows tuning of the photoluminescence of the 480°C Qdots to emission wavelengths close to the 1.55μm target. Double capping consists of a growth interruption under an arsenic/phosphorous (As_2/P_2) flux. The aim is to reduce the tendency of As atoms in InAs regions to be replaced by P, which is believed to be the cause of inhomogeneous broadening of the emission spectrum in the InAs/InP Qdash system. The typical photoluminescence line-width for InAs/InP Qdashes is 100meV, which is much larger than that for InAs/GaAs Qdots. This can be reduced to about 62meV with double capping [2].

A 1mm cavity laser structure consisting of five Qdot layers on the miscut (001) substrate, separated by $Ga_{0.2}In_{0.8}As_{0.435}P_{0.565}$ spacers, was grown that produced room-temperature electroluminescence at 1.62μm. The lasing threshold current density was 1.06kA/cm^2 (206A/cm^2 per layer). The device measured 1x0.1mm. The output power is not reported.

Dashed hopes

The INSA group sees their results as being comparable to those of Alcatel-Thales researchers who achieved a 110A/cm^2 per layer current density threshold for an InAs Qdash laser on nominal InP(001) substrates. The Alcatel-Thales III-V Lab in France has worked on InAs/InP quantum dash based lasers and optical amplifiers using a variety of dots and dashes.

To improve characteristic temperature values and dynamic performance, the Alcatel-Thales group has found p-doping of the barriers with beryllium in the active Qdash layer to be useful [3]. High characteristic temperatures indicate less degradation in performance as temperature increases. Less variation in performance with temperature offers the potential for simpler/less costly control circuitry.

Six Qdash layers were separated by 40nm barriers (~$4x10^{18}$/cm^2 beryllium) within two 80nm separate confinement heterostructures (SCHs). Broad area (BA) and buried ridge stripe (BRS) Fabry-Perot (FP) laser structures were produced (Figure 2). Characterization of a series of BA devices suggests an unacceptably large value for the threshold current density of ~10kA/cm^2 for an infinite length cavity (Figure 3). This is connected with the increase in non-radiative (Auger) recombination as p-doping increases.

However, the characteristic temperature (T_0) is higher than that for an undoped reference device — 135K in the range 25–85°C for a 425μm BA device, compared with ~80K for undoped barriers. For the same range and continuous-wave operation with more than 6mW output, T_0 is 103K. These values are better than for AlGaInAs-based multi-quantum well structures that have been explored to increase the generally poor characteristic temperature of InP-based LDs.

The relaxation frequency, indicating better dynamic performance, is also improved from 7.5GHz for the

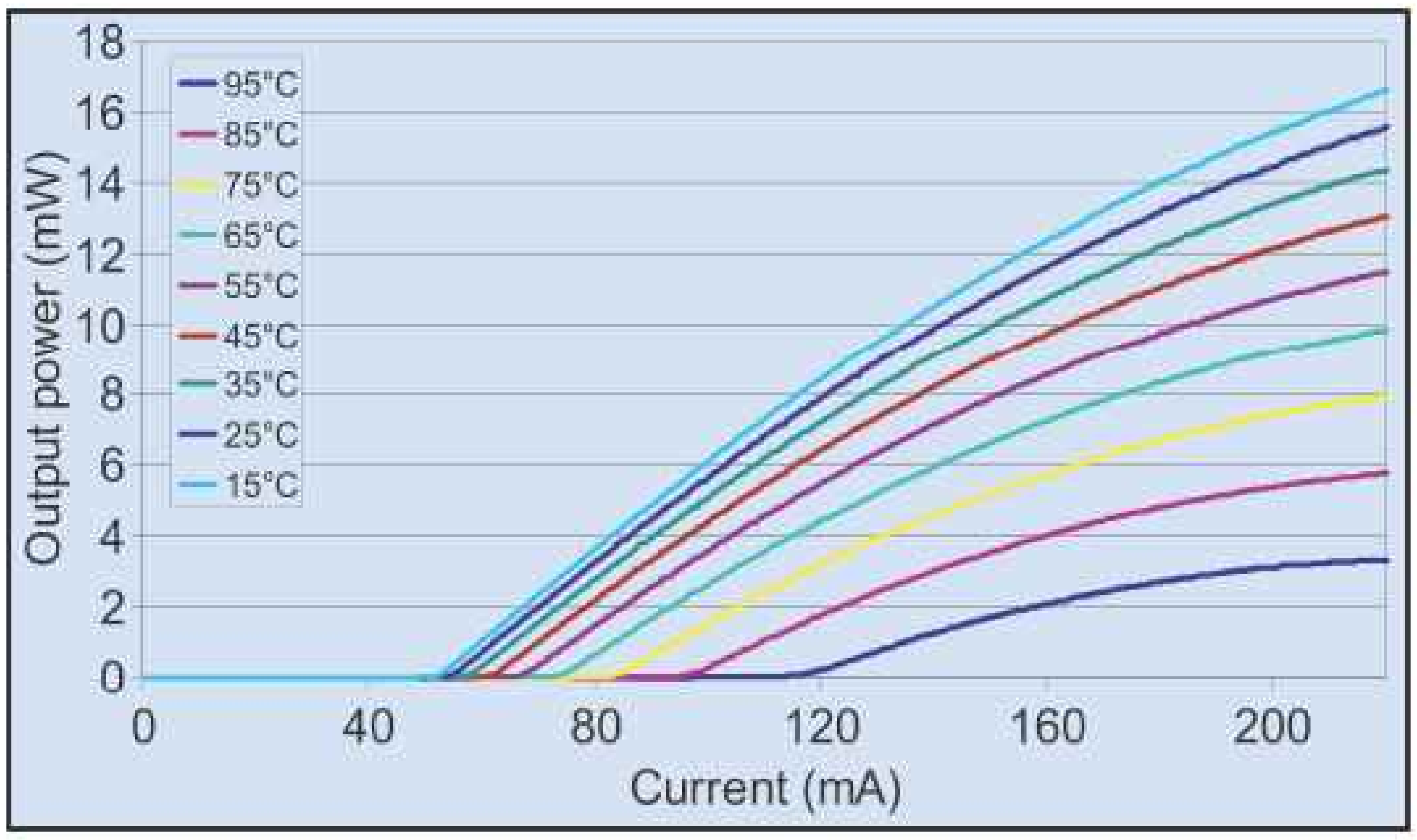

Figure 3. Temperature dependence of output power versus current (L–I) for Alcatel-Thales III-V Lab's 1.5x600μm high-reflectivity coated LDs using p-doped barriers at various temperatures (15–95ºC in steps of 10ºC). High temperature degrades output power, along with increasing threshold current.

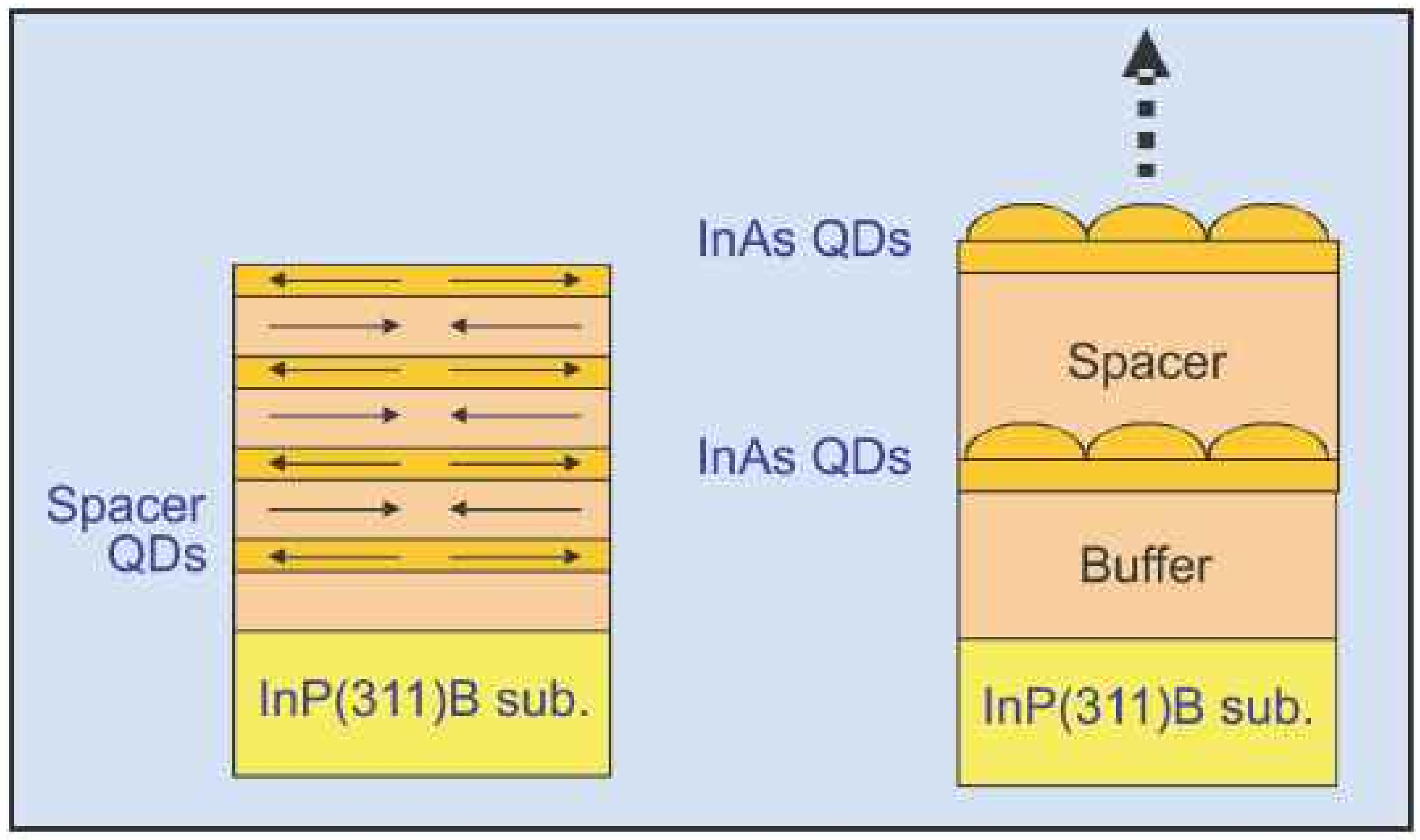

Figure 4. Compensating spacer layers are used by Japan's National Institute of Information and Communications Technology (NICT) to reduce the average strain in quantum dot structures. The buffer ($In_{0.52}Al_{0.48}As$) is lattice matched to the InP substrate. The spacer is a quaternary alloy (InGaAlAs).

undoped device to 13.5GHz at an injected current of 200mA on the BRS formation. "To our knowledge, this value is the highest relaxation frequency ever reported in CW operation for InP-based Qdot and Qdash lasers," say the researchers. Similar techniques have been used to develop semiconductor optical amplifiers at Alcatel-Thales [4].

Alcatel-Thales III-V Lab has also contributed to work by the French CNRS Laboratoire de Photonique et de Nanostructures (CNRS/LPN) on InAs/InP Qdash mode-locked lasers that have repetition rates greater than 300GHz with low timing jitter down to 400fs [5]. Such devices are seen as having potential for applications such as ultra-high bit rate (320Gb/s) clock recovery, terahertz generation based on photoconduction, and microwave photonics.

Further work at CNRS/LPN, with some contributions from Alcatel-Thales III-V Lab, has been on developing Qdash-based passive mode-locked lasers. One device produced sub-picosecond ~1.5μm light pulses with a 346GHz repetition rate (claimed to be a record [6]).

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Rather than using more complicated arrangements with special absorbers or multiple sections, as is often used to create mode-locking, a simple single-section laser diode was used. This avoids extra processing steps.

The Qdash structure was grown using GSMBE on sulfur-doped (001) InP (n-type). Six layers of InAs dashes make up the active regions separated by 80nm barriers and with 40nm SCH layers. Undoped $Ga_{0.2}In_{0.8}As_{0.4}P_{0.6}$ layers (E_g=1.17μm) lattice matched to the substrate were used for these barriers and SCH layers. BA and BRS lasers were then created with InP cladding and GaInAs contact layers.

The laser threshold current density, from the extrapolation of measured data to infinite length, was 0.68kA/cm^2 (110A/cm^2/layer). The characteristic temperature was 70K for the temperature range 20–80ºC.

BRS lasers with cavity lengths of 120μm and 170μm were investigated for mode locking. The wavelengths were 1.53μm and 1.55μm, respectively. The threshold was 6mA in both cases. Stable mode-locking was observed for currents in the range 60–250mA. The repetition rates were 346GHz (pulse width 560fs at 217mA) and 245GHz (pulse width 870fs at 180mA) for the 120μm and 170μm cavities, respectively. The mode locking is attributed to enhanced four-wave mixing in the material system.

In addition to general mode-locked laser applications above, monolithic semiconductor mode-locked lasers (MLLs) could be of use in optical interconnects and low-noise electro-optic sampling.

Another group working on mode- (and injection-) locking with a view to applications is the University of New Mexico's Center for High Technology Materials, where Qdot and Qdash systems are both being developed on GaAs and InP substrates. Recent work has focused on accurately modeling such systems to enable system design optimization for features such as modal gain, low losses, line-width enhancement, elimination of pre-resonance dip, modulation bandwidth, etc. For injection locking, low temperature and high bias current is favored for the slave Qdash laser. Some of this research is financed by the US Air Force Research Laboratory (ARFL).

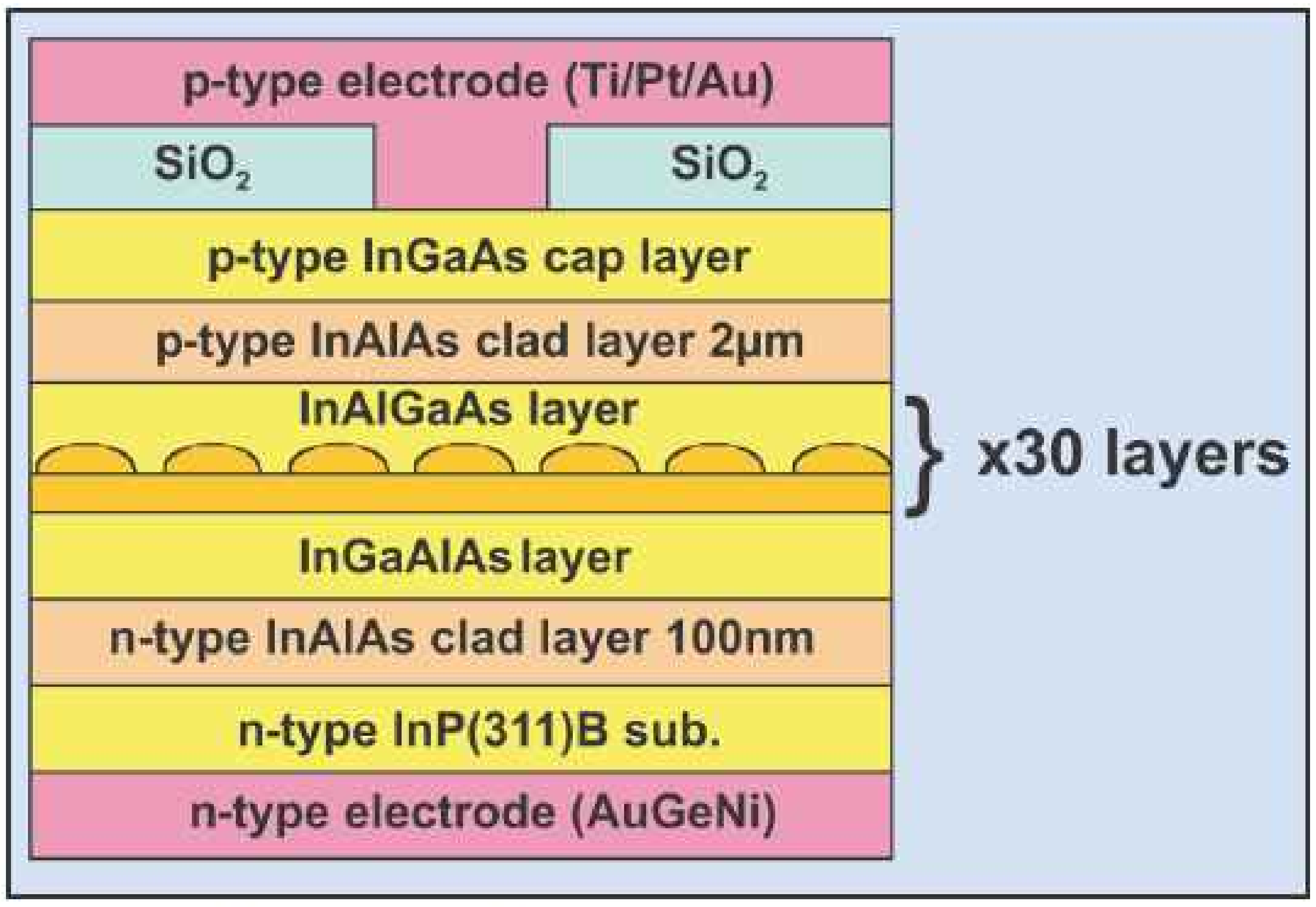

Figure 5. NICT laser diode structure, targeting devices with a line width of 50mm and cavity length of 600–1400μm.

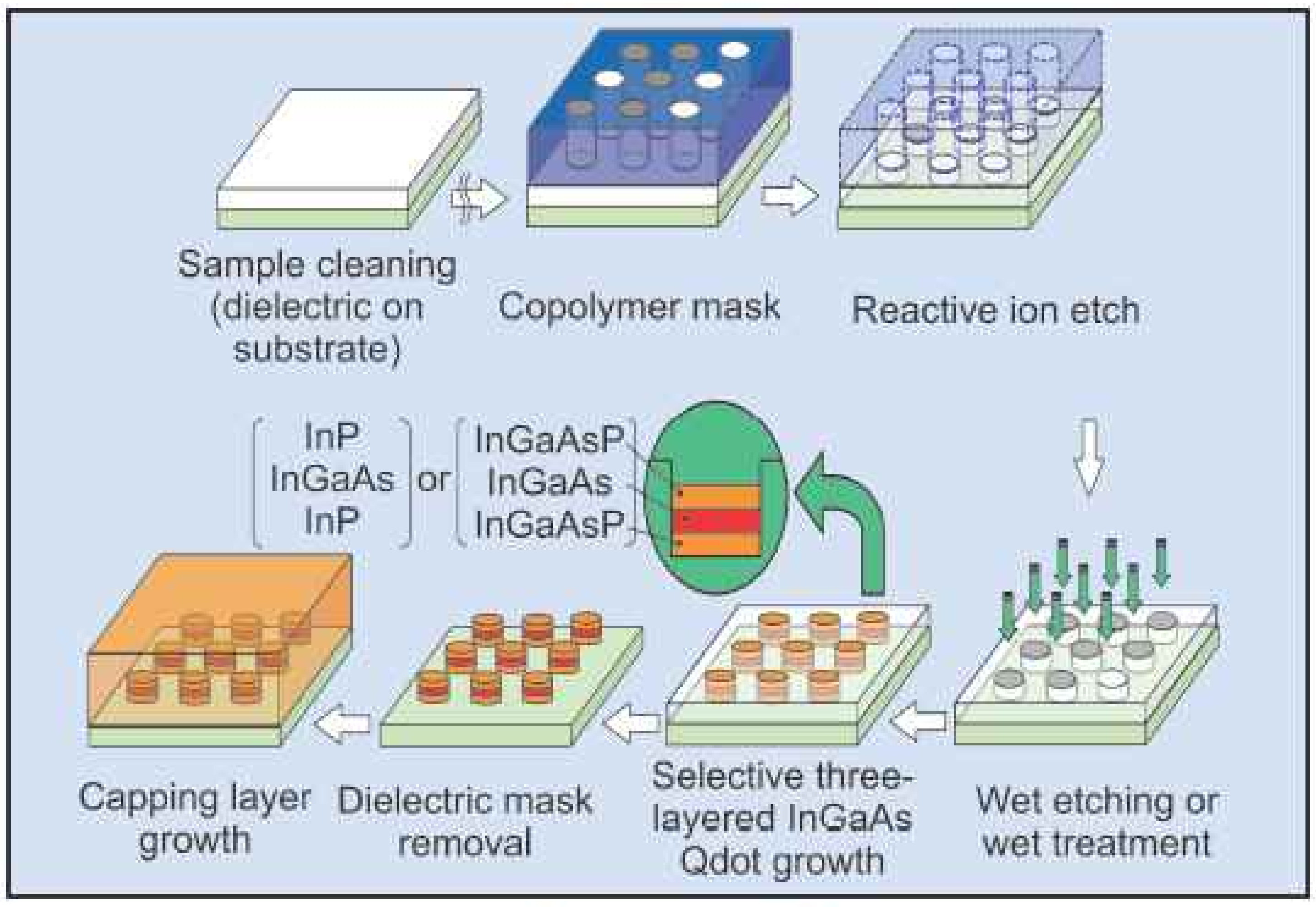

Figure 6. University of Wisconsin-Madison process flow for producing Qdots using oriented block co-polymers.

Stacking

Japan's National Institute of Information and Communications Technology (NICT) has been looking at the possibilities of increasing Qdot densities through stacking on InP(311) substrates [7]. The problem that NICT has been focusing on is the accumulation of strain that often occurs when layers of InAs Qdots are built up on InP(311)B substrates.

The NICT approach has been to separate the Qdot layers with compensating spacer layers with the opposite strain so that the strain is reduced across the structure (Figure 4). The spacer layer that is used is a quaternary $In_xGa_yAl_{1-x-y}As$ material with y~0.2. LDs produced using 30 layers of Qdots (Figure 5) resulted in a current threshold of 517.5mA (57A/cm^2 per dot layer) and a slope efficiency of 0.052W/A at room temperature. The lasing wavelength was about 1530nm. The characteristic temperature (T_0) was a high 113K.

Beyond self-assembly

Researchers at the University of Wisconsin at Madison (UW-Madison) have taken a somewhat different approach to producing Qdot structures on InP. The usual techniques often depend on the 'self-assembly' of the dots on the growth surface. UW-Madison has instead developed patterning methods to produce useful nano-confinement structures.

One approach uses di-block co-polymer masks — i.e. organic materials that, under treatment, polymerize into regions with different etching properties. For example, polystyrene-b-poly(methyl methacrylate) (PS-b-PMMA) can be spun onto SiO_2 dielectric and, after ultraviolet radiation, the material polymerizes into PMMA cylinders in a PS matrix [8]. The cylinders can be removed by a reactive ion etch (RIE) to form a mask for wet etching into the dielectric. The mask is then removed and the holes in the dielectric filled with III-V material to produce Qdots (Figure 6).

Unlike previous attempts to produce patterned Qdots on InP that resulted in 60nm diameter structures, some 99.5% of the dots produced by UW-Madison come in at less than 34nm. The density of the dots is only marginally less than those produced using self-assembly techniques.

Photoluminescence characterization has been carried out on InGaAsP/$In_{0.53}Ga_{0.47}As$/InGaAsP dots in an InGaAsP SCH (Figure 7). The dot emission peak could be varied between 1400nm and 1600nm by varying the InGaAs layer thickness from 1nm to 25nm. By changing the confining InGaAsP layer of the Qdot to

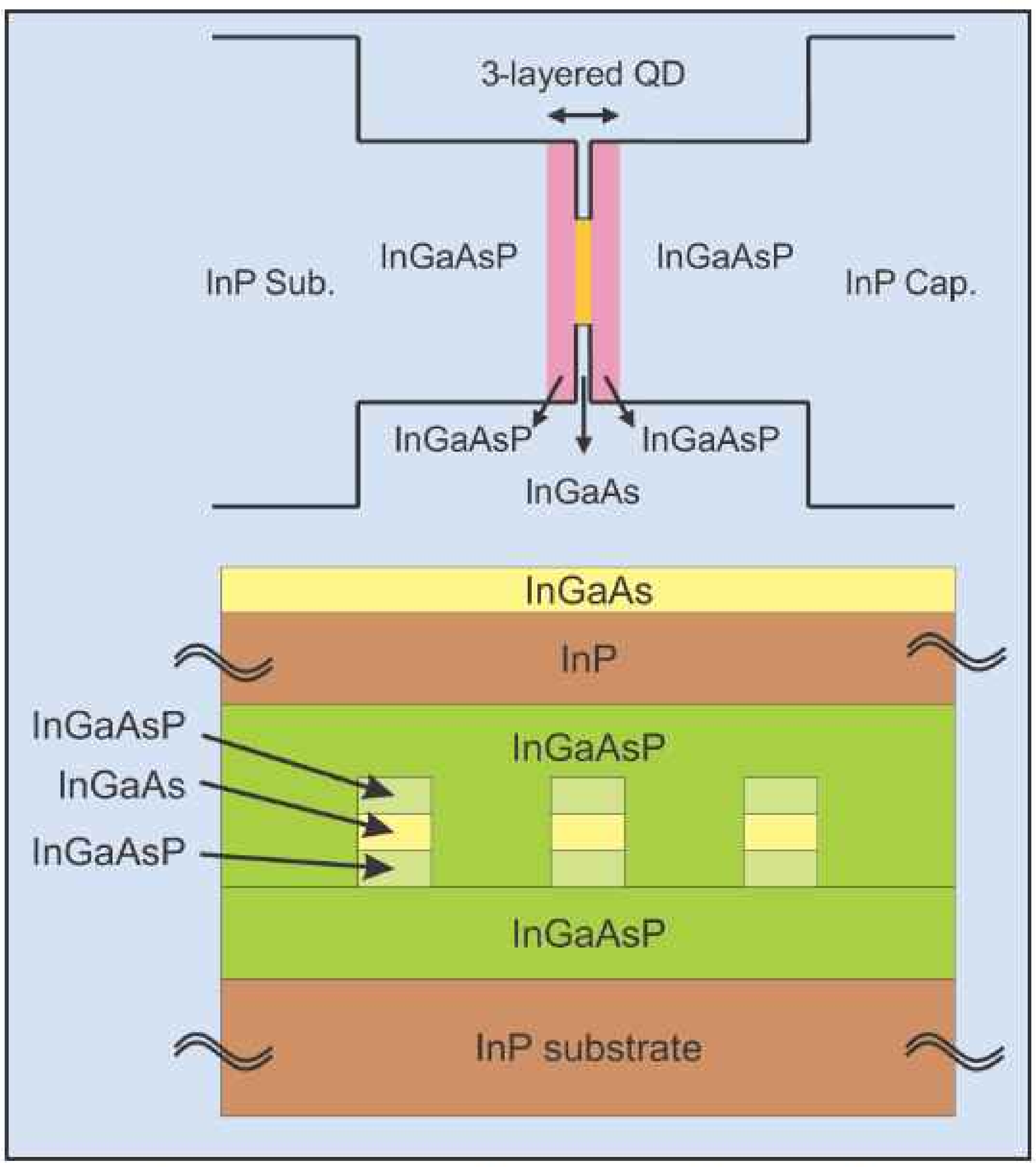

Figure 7. Madison's InGaAsP/InGaAs/InGaAsP Qdots incorporated into SCH as needed for LDs.

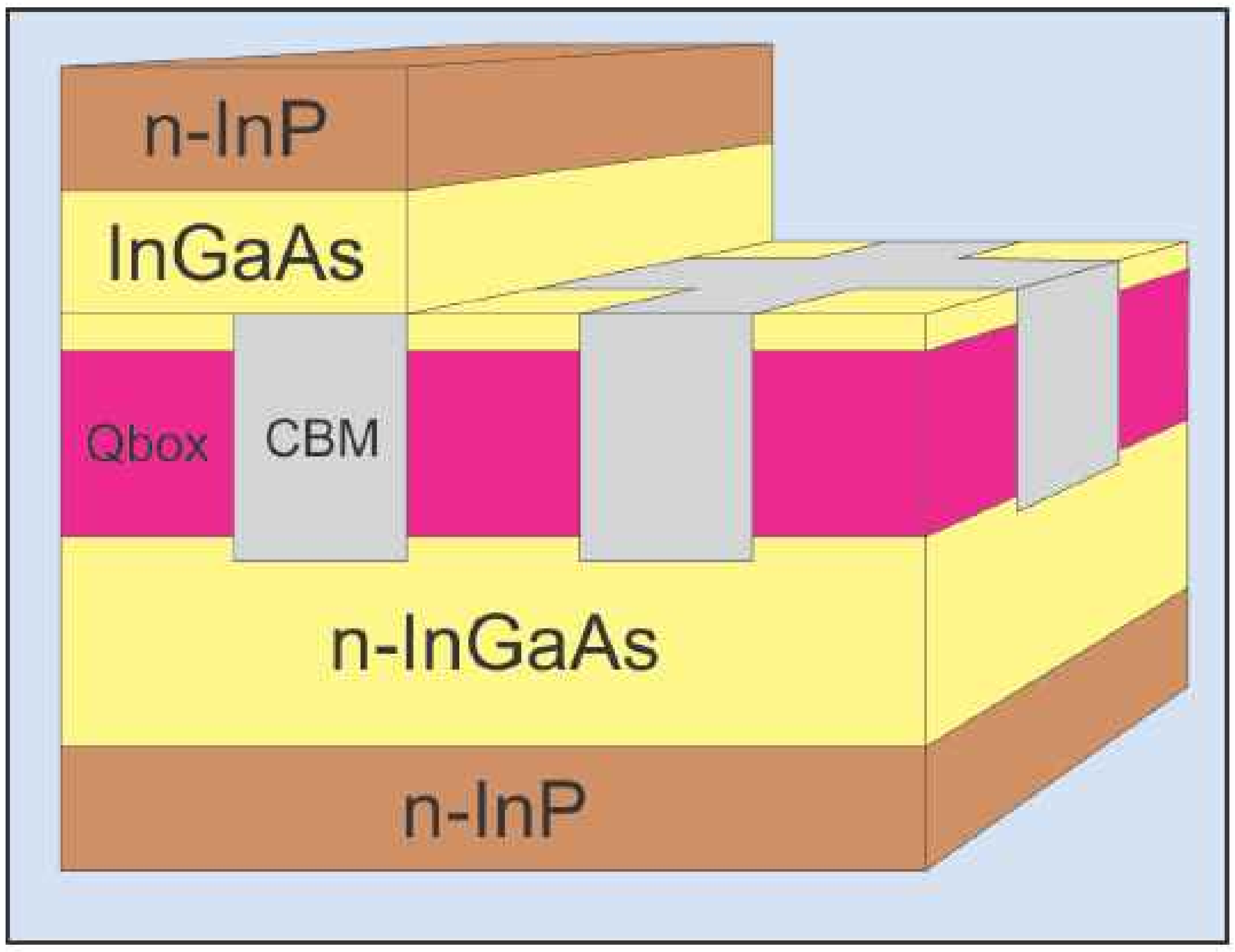

Figure 8. Madison Qbox structures.

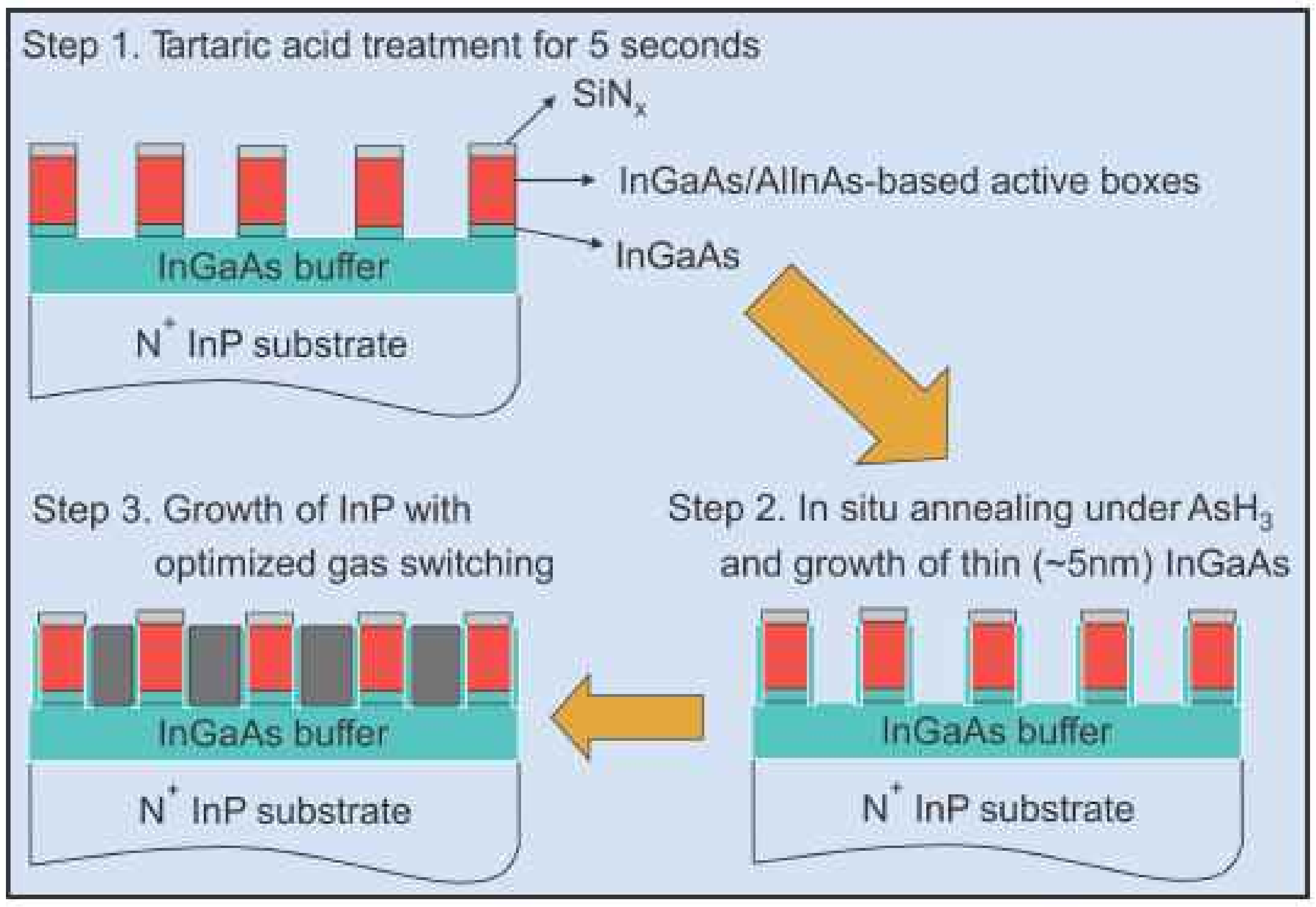

Figure 9. Madison technique for regrowth of current blocking material.

InP, a near 90x increase in brightness in PL was achieved, although the peak wavelength also reduced from 1556nm (full-width half maximum 63meV) to 1474nm (FWHM 34meV). Plans are afoot to produce lasers based on such Qdots.

Another structuring technique being explored by UW-Madison is to etch through an active layer to create quantum 'boxes' (Figure 8). The 30nm x30nm x56nm boxes are separated by an iron-doped semi-insulating InP current-blocking material that is regrown in the space left by the etch. The patterning for the reactive ion etch is achieved using a SiN$_x$ mask. The active layer consists of boxes of InGaAs/AlInAs. It is important to develop suitable passivation techniques for the etch surfaces (Figure 9) before regrowing the CBM [9]. Capacitance–voltage measurements have been made to characterize the passivation effectiveness, and the first electroluminescence experiments on the mid-wave infrared intersubband transitions (between quantized states in the conduction band) have found peaks at about 3.5 and 3.8μm, as expected from models.

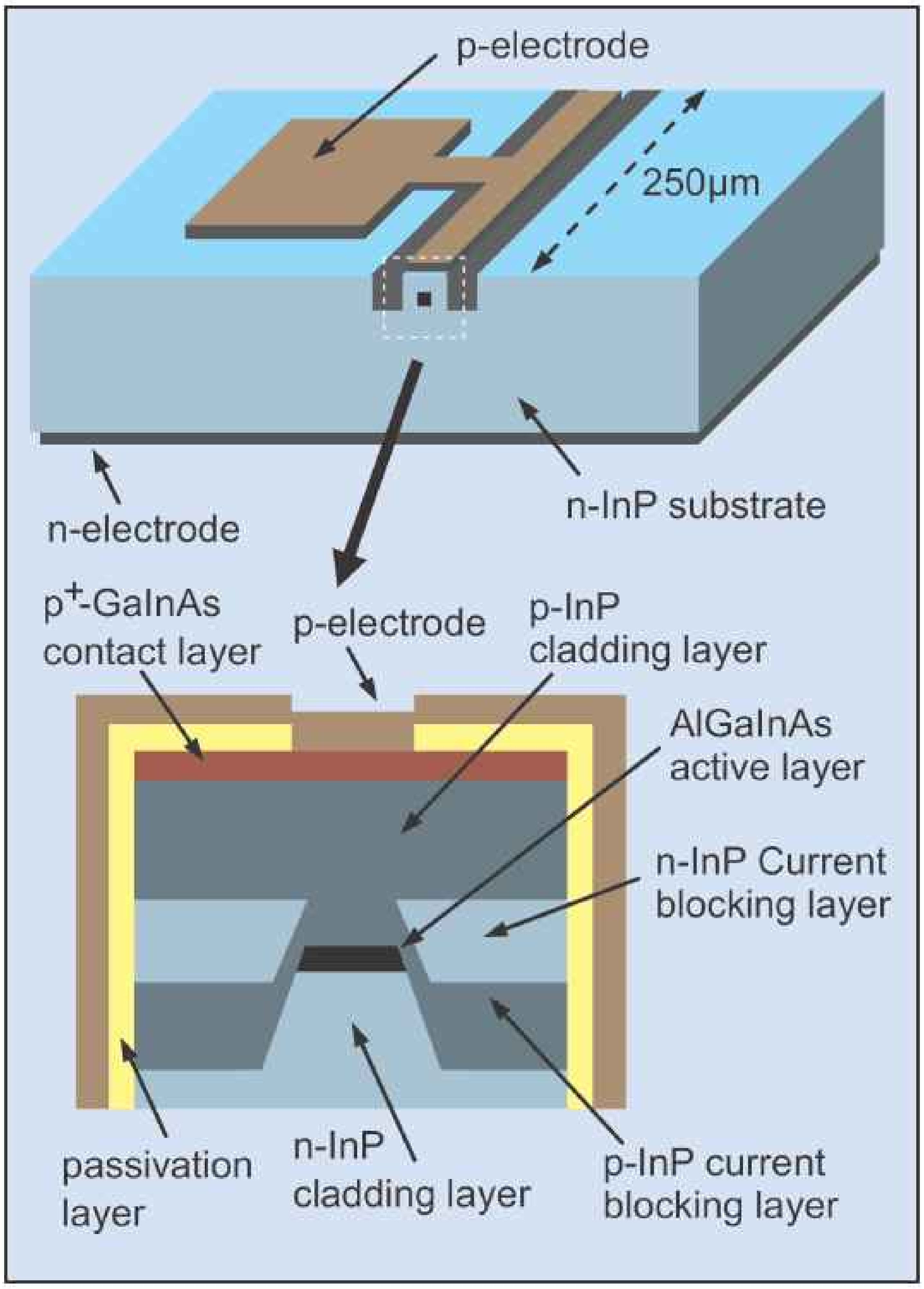

Figure 10. Schematic structure of an AlGaInAs/InP buried heterostructure DFB laser diode.

Other InP laser diode stories from IPRM

While much of the laser diode research reported at the recent Indium Phosphide and Related Materials conference (IPRM, 10–14 May 2009) centered on confined quantum dot/dash systems in indium phosphide (see above), there were a number of other developments presented. Two examples follow.

● ESD

Sumitomo Electric Industries (SEI) has been addressing electrostatic discharge (ESD) issues in aluminum gallium indium arsenide on InP substrate (AlGaInAs/InP) laser diodes (LDs) aimed at optical communications applications (Figure 10). Company researchers have managed to produce buried heterostructure (BH) Fabry-Perot LDs with estimated lifetimes of 240,000 hours. Protection circuits can be used in LD modules, but SEI is interested in applications that use isolated LD chips. Such work has been carried out before on GaInAsP/InP LDs, but not the 1.3μm AlGaInAs/InP distributed feedback LDs that SEI is working on [10].

The 'human body model' (e.g. finger contact) with voltages from 0.5kV to 3.0kV was chosen as the most suitable for LD ESD tests. It was found in a test of

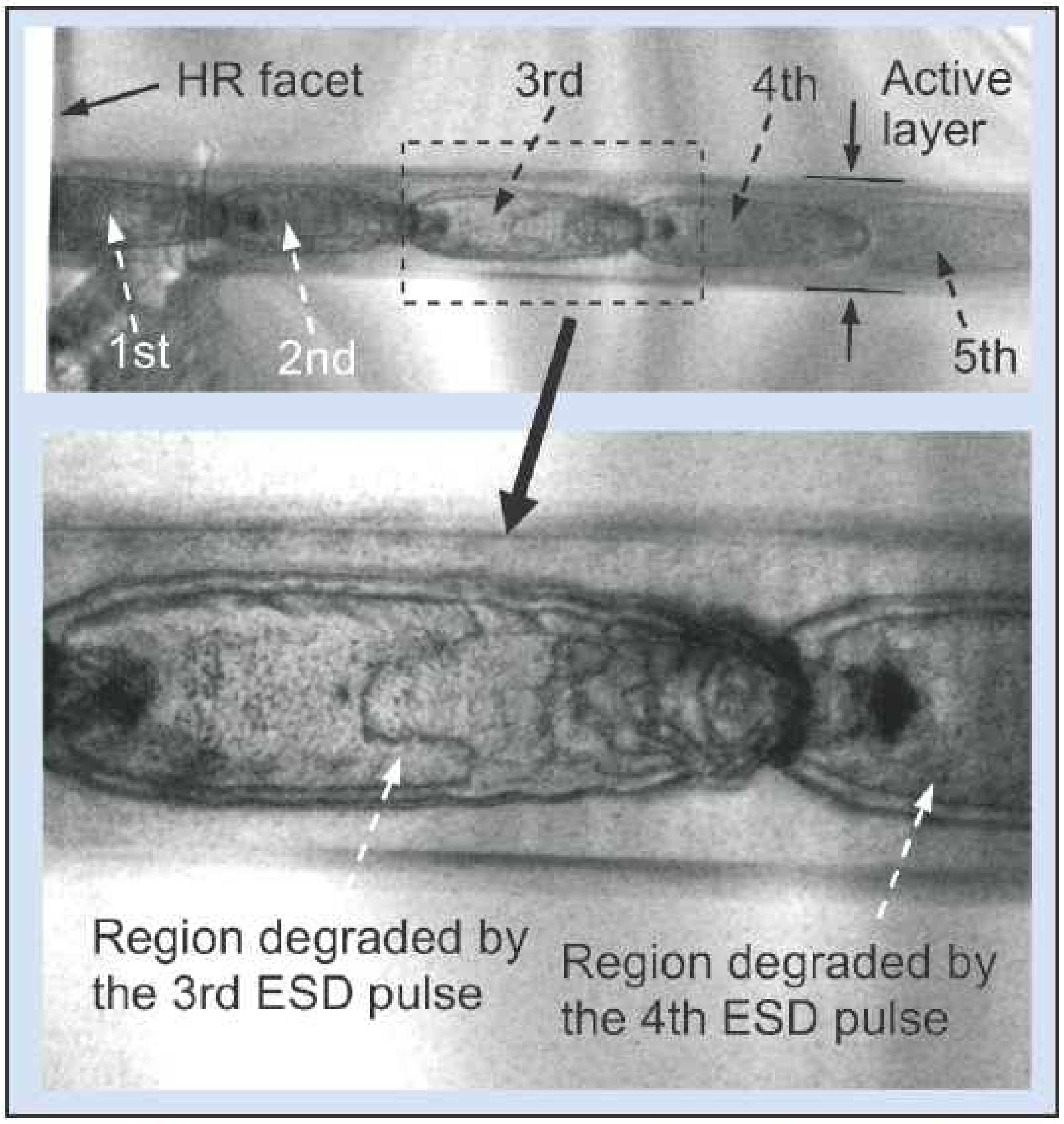

Figure 11. TEM plan image of an AlGaInAs/In PLD degraded by 0.5kV forward-biased ESD test at Sumitomo Electric Industries.

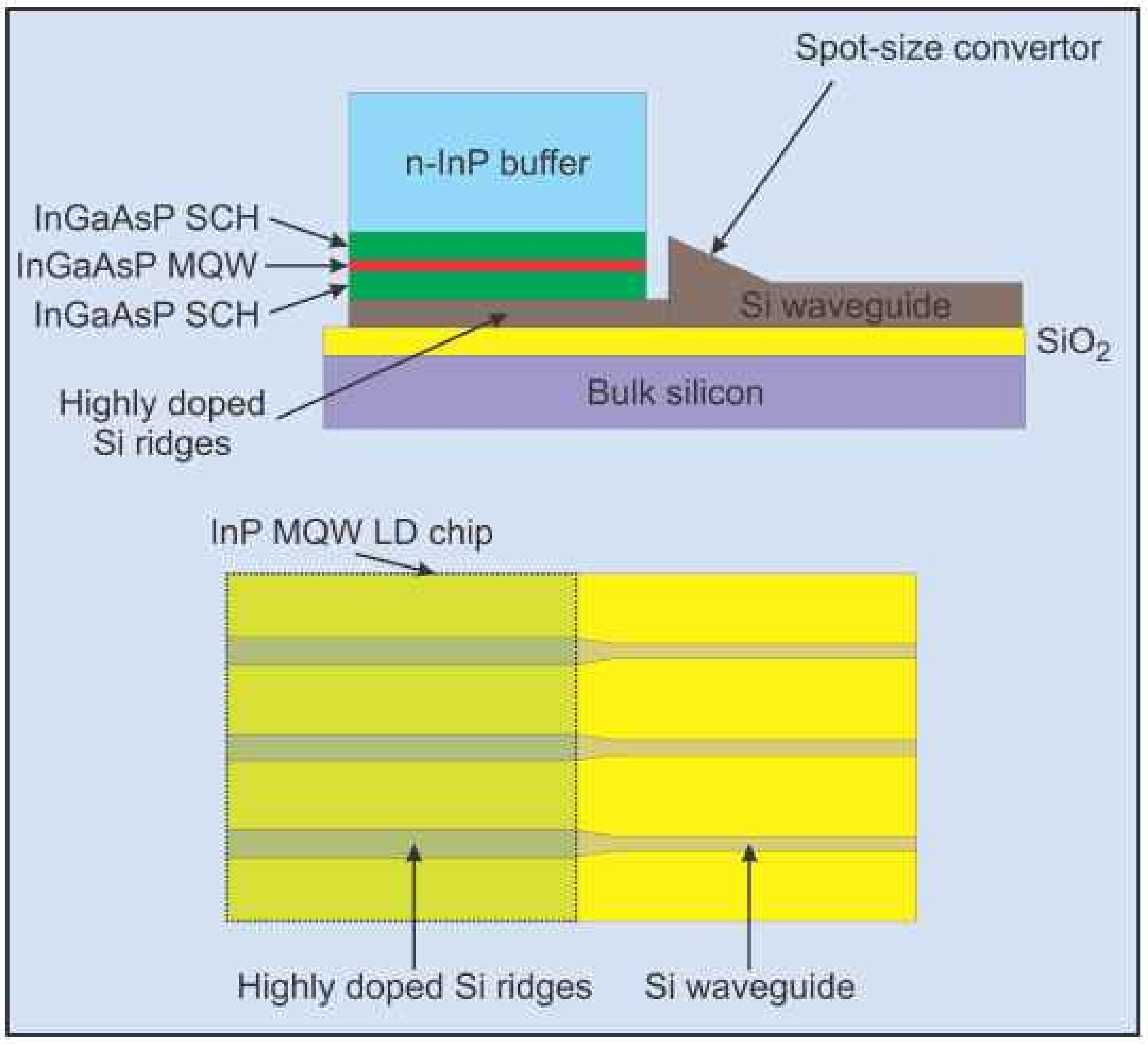

Figure 12. Side and top schematic views of hybrid of InP-based laser and silicon waveguide structure as developed by University of Tokyo.

33 devices that a forward bias of 0.5kV degraded some devices, while for reverse bias a voltage above 2.5kV was needed. For normal use, 1kV ESD tolerance is considered sufficient, so only forward-bias ESD is a concern for these devices.

Further investigation of the electroluminescence of a degraded device revealed a dark region of ~10μm in the active layer near the high-reflection facet (Figure 11). The investigations suggest that the active layer melted under absorption of the intense laser light. The researchers successfully applied a technique previously used for GaInAsP/InP LDs — a thin passivation layer of aluminum was applied to the facet to reduce recombination levels near the high-reflectivity coating, reducing the intensity of light and hence the tendency to produce melting in this surface region. This reduced the degradation rate at 1kV ESD from 40% for unpassivated devices to 0%.

● Hybrids

University of Tokyo researchers have been working on plasma-aided direct bonding of InP-based multi-quantum wells (MQWs) to silicon-based substructures to create self-aligned laser components [11]. Alignment is particularly important for optical systems to ensure that power losses and threshold currents are minimized, and that flexible tuning is achieved for single-mode and other modes of operation.

The QW system consists of InGaAsP material, along with separate confinement heterostructures (SCHs) and InP buffer. The silicon-on-insulator structures include waveguides, spot-size converters, and highly doped silicon ridges. The connection between the MQW system and waveguide is a parallel butt-end arrangement.

The ridge structures can be produced either during growth on the InP structure, or on the silicon structure. These structures provide one of the electrode contacts for providing current injection into the MQW. By adding distributed Bragg reflection (DBR) or distributed feedback (DFB) structuring to the ridge, single-mode or frequency tuning features can be achieved. The bonding is described as 'almost alignment free'.

The refractive index of the phosphorous-doped silicon ridge (3.1–3.4) is higher than that for normal InP cladding and hence provides extra confinement of light in the lateral MQW active region. ■

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.

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