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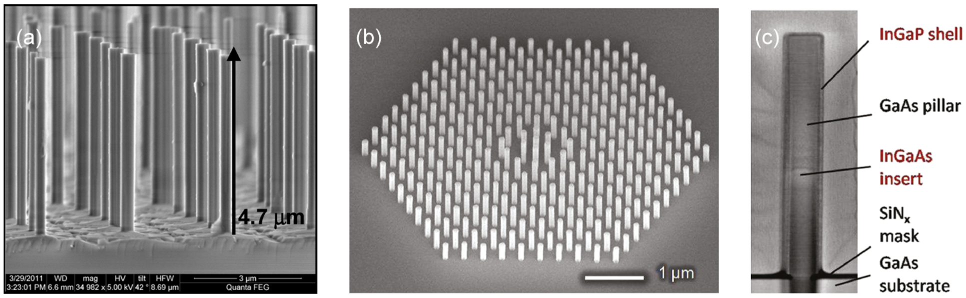

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Breakthroughs in Semiconductor Lasers

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Abstract: The latest breakthroughs on the frontiers of semiconductor laser capabilities are presented. Achievements including the impressive advances in high-speed lasers with low pJ/bit energy consumption, high-power vertical external cavity surface emitting lasers (VECSELs), advances in III-nitrides, record-high temperature operation quantum dot lasers, the longest wavelength Type-I quantum well lasers to date, and the fascinating field of nanolasers with ultralow volume and threshold are all discussed.

Index Terms: Mid-infrared (IR) lasers, nanolasers, vertical cavity surface emitting lasers (VCSELs), semiconductor lasers, vertical external cavity surface emitting lasers (VECSELs), quantum dots (QDs), III-nitrides.

This review covers some of the most notable advances for semiconductor lasers in 2011. In particular, the latest results on high-power vertical external cavity surface emitting lasers (VECSELs) are reviewed with an emphasis on heat management. In terms of low-dimensional semiconductor lasers, the impressive performance of high-temperature ridge-waveguide quantum dot (QD) lasers is highlighted. Advances in the field of mid-IR lasers is also visited as well as breakthrough results pertaining to nanoscale lasers including bottom-up and top-down fabricated devices. Breakthroughs associated with the III-nitride material system are also addressed. First, we begin by reviewing the most significant results for high-speed and energy-efficient vertical cavity surface emitting lasers (VCSELs).

With what seems like an insatiable demand for faster access to information by modern society, so comes the inevitable need for the rapid and efficient transfer of data. It is expected that optical interconnects at the chip level are needed within a decade. The VCSEL is one of the candidates being touted as the light source to meet this challenge [1]. At the standard local area network (LAN) wavelength of 850 nm, high speeds reaching 40 Gbit/s have already been reported [2]. In parallel, there has been an impetus to move to longer wavelengths such as 980 nm an 1100 nm. Typically, VCSELs emitting at these wavelengths are based on compressively strained InGaAs quantum wells which have the advantage of higher differential gains and relaxation resonance frequencies and, therefore, the possibility of larger bandwidths. At 980 nm, the Technical University of Berlin has demonstrated error-free nominal data transmission rates of 40 Gbit/s up to temperatures of 85 °C, the highest data rates reported for VCSELs to date [3]. The origin of the improved performance has been cited as arising from a combination of several factors including optimized doping profiles and gain-cavity detuning, a binary GaAs bottom mirror and a shortened $\lambda/2$ cavity.

Currently, in terms of the energy-efficiencies required of optical interconnects in data centers, the International Technology Roadmap for Semiconductors demands lasers which exhibit a dissipated energy/bit in the region of $\sim$100 fJ/bit (100 mW/Tb/s) [4]. Previous research has shown that sub 500 fJ/bit performances can be achieved using standard VCSEL technology at 980 nm and at 850 nm [5]. Research on such energy-efficient light sources in 2011 has been intense with Furukawa Electric Co. demonstrating 140-fJ/bit operation at a data rate of 10 Gbit/s at 1060 nm [6]. The real breakthrough in low power consumption VCSELs has been pioneered by a collaboration between the Technical University of Berlin and VI Systems GmbH from which the first sub 100 fJ/bit results have emerged. This result represents the most power efficient high-speed directly modulated light sources to date and were based on oxide confined GaAs-based VCSELs. The devices emit at 850 nm and operate at 17 Gb/s and the energy to data rate ratio ranges from 81–83 fJ/bit, while at 25 Gb/s, it becomes 99-117 fJ/bit for temperatures of 25 °C to 55 °C, respectively [5]. The impressive strides in energy-efficiency have been associated with reducing the operating currents through an optimization of the mirror doping profiles with a resultant reduction in the internal losses.

The lure of the VECSEL stems from its exceptional beam quality and high output powers coupled with a wavelength range spanning the infrared spectrum all the way to the visible [7]. The latter wavelengths are generated via nonlinear optical elements placed within the VECSEL cavity through frequency doubling and quadrupling. As a consequence of this flexibility, applications are wide, encompassing, for example, laser radar systems, chemical sensing and infrared countermeasures. Additionally, near-IR QD-based VECSELs can be used to provide high power at 1200–1280 nm [8], which is suitable for noninvasive selective photothermolysis of adipose tissue [9] or which can be frequency-doubled to reach red light for laser TV. In general, heat management has been the key focus in driving improvements in output power [7], [10]. The VECSEL is typically bonded using indium solder to a high thermal conductivity heat spreader such as diamond. The highest power to date of 100 W, reported in 2011 was achieved through a collaboration between researchers at the University of Arizona and Phillips University in Marburg based on 1040-nm InGaAs quantum wells [11].

The VCSEL was the first laser with a wavelength scale optical mode. Now stellar progress has been accomplished worldwide in the miniaturization of lasers in just the past few years using metals to form the laser resonator. Due to the small size and strong confinement in these laser structures, certain familiar concepts in semiconductor-laser physics needed to be carefully examined to determine their validity or implications at the nanoscale; therefore a new generation of laser designers had to get educated on the fundamentals of laser quantum engineering[1] [12], [13]. A portion of these devices now show lasing in cavities significantly smaller than the wavelength of light in all three dimensions with the optical mode being much smaller than what is permitted by the diffraction limit. For instance, the first report of lasing in metallic nanostructures occurred in 2007 and now this research area has exploded with various groups reporting impressive results based on plasmonic and metal-cavity nanolasers [12], [14]. Electrical injection of metal cavity lasers with a dimension less than a wavelength in one or two dimensions has also been demonstrated. Other approaches for nanolasers including cavities based on coaxial waveguides have been realized with thresholdless lasing operation at $\sim$1370 nm in a single mode coaxial cavity of subwavelength size at cryogenic temperatures [15]. Nanolasers formed from top-down or bottom-up processed wires fabricated in a variety of material systems have made notable progress in recent months. As shown in Fig. 1(a), top-down GaN nanowire lasers emitting at 370 nm have achieved single-mode operation for a cavity with a diameter of 130 nm and a length of 4.7 μm [16]. The optically pumped laser threshold is about 250 kW/cm^2. The bottom-up GaAs/InGaAs/GaAs nanopillars shown in Fig. 1(b) are encased in an InGaP shell and are arrayed to simultaneously form a photonic band gap and the laser gain region [17]. The lasers operate single-mode at room temperature with an optically pumped threshold of 625 W/cm^2. MOCVD-grown InGaAs nanopilllars lasers emitting at 950 nm have also been achieved on a silicon substrate [18]. These lasers, which are particularly

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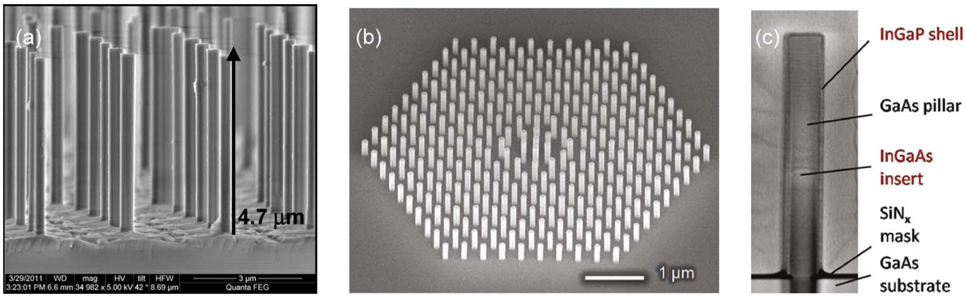

Fig. 1. (a) SEM of top-down GaN nanowire array (courtesy of Sandia National Labs), (b) bottom-up fabricated GaAs nanopillars and (c) cross-sectional STEM of a nanopillar showing the InGaAs insert located at the center of the pillar and InGaP shell (reprinted from [17] with permission from the ACS).

suited for high-density integration with CMOS electronics, depend on a helically propagating cavity mode in a subwavelength size cross-sectional pillar.

Historically, the emission wavelength range between 3–4 μm has been a graveyard for the semiconductor laser. Three different technologies currently compete in this arena including quantum cascade lasers (QCL), interband cascade lasers (ICL), and Type-I quantum well lasers, which are expertly compared in [19]. Progress in extending the wavelength of emission for Type-I quantum well lasers on GaSb substrates has been remarkable [20]. The most recent success comes from the Walter Schottky Institute which has achieved room temperature pulsed-mode lasing at 3.73 μm [21]. The authors attribute the extended wavelength performance to the use of quinternary AlGaInAsSb barriers around a 1.46% strained GaInAsSb quantum well. Potential applications include atmospheric monitoring for such gases as ozone, sulfur dioxide, and methane in the water-free absorption window. Strain-compensated InGaAs/AlAsSb QCLs on InP substrate have demonstrated wavelengths as short as 3.05 μm at 295K. For longer emission from 3.3–3.7 μm, QCLs have exhibited up to 20W output power at 285K, showing their clear advantage is output power in this wavelength range [22]. Regarding a viable source of THz radiation, THz QCLs operating significantly above the temperature limit (photon energy/Boltzmann constant) have been reported. These and other recent advances on Terahertz QCLs are extensively reviewed in [23].

GaN and its alloys have become the standard material system used for producing short-wavelength visible light-emitting devices; however, this material system has not come without its challenges. Charge separation effects have plagued InGaN QW lasers. Traditional c-plane InGaN QWs with large overlap design have been adopted for addressing the charge separation effect by exploiting staggered InGaN QWs [24]. Lasing performance comparable with the state-of-the-art conventional c-plane InGaN QW lasers has now also been attained in nonpolar/semipolar InGaN QW lasers [25]. There has been no electrically injected laser devices realized in the deep-UV to mid-UV laser wavelength regime (~220–320 nm). The challenges associated with these impediments are rooted in an insufficient understanding of the gain properties of the active region as well as challenges in material epitaxy. Nonetheless, in recent years, considerable theoretical progress has been made in understanding of the gain properties of high Al-content AlGaN QWs for deep UV lasers. Leveraging on these foundations, Taniyasu et al. have experimentally demonstrated a significant TE gain at deep-UV wavelengths based on AlN-delta-GaN QWs [26]. In related work, substantial results have been reported for current-injected GaN-based VCSELs based on a combination of hybrid dielectric DBRs and epitaxially grown DBRs [27].

Finally, one of the perpetual challenges since the inception of the semiconductor laser has been the ability to operate at high temperature. Recently, QD Laser Inc. has reported on a 1.2-mm-long QD edge-emitting ridge waveguide laser capable of ground state lasing up to 220 °C while at the same time maintaining 1 mW of output optical power [28]. This feat makes it the highest operating temperature for any commercially available semiconductor laser. The realization of such performance required a combination of a reduced dot dispersion and increased areal dot density. The device also featured high-reflectivity coatings on both laser facets. The optimized material epilayers consisted of eight InAs QD layers, featuring a dot density of 5.9×10^{10} cm^{-2} in each stack, and included partially *p*-doped GaAs barriers. In addition, because the ground state and first excited state were separated by a large amount (80 meV), excited state lasing at very high temperatures was suppressed. Potential hot environment applications include oil and gas exploration, as well as incorporation in energy-efficient optical interconnects.

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