EDITORIAL

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EDITORIAL

Focus on advanced semiconductor heterostructures for optoelectronics

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Abstract. Semiconductor heterostructures are the basic materials underlying optoelectronic devices, particularly lasers and light-emitting diodes (LEDs). Made from various III–V-, II–VI-, SiGe- and other compound semiconductors, modern semiconductor devices are available for the generation, detection and modulation of light covering the entire ultra-violet to far-infrared spectral region. Recent approaches that introduced multilayer heterostructures tailored on the lower nanometre scale made possible artificial semiconductors with new properties, such as extended wavelength coverage, that enabled new applications. Together with ongoing progress on wide-gap semiconductors, the optical wavelengths accessible by semiconductor devices are steadily expanding towards the short-wavelength ultra-violet regime, as well as further into the far-infrared and terahertz spectral regions. It is the aim of this focus issue to present cutting-edge research topics on the most recent optoelectronic material and device developments in this field using advanced semiconductor heterostructures.

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1. Introduction

Semiconductor optoelectronic emitters are based on radiative transitions occurring in heterostructures that provide electrical and optical confinement. Usually, light-emitting diodes (LEDs) and lasers are based on interband transitions in direct semiconductors such as GaAs, InP, GaN or GaSb. Using not only lattice-matched but also strained or strain-compensated alloys in quantum well structures, huge bandgap energy ranges and equivalent emission wavelength ranges can be covered without gaps by these material systems. Since 1994, intersubband transitions have also been exploited for laser operation in the so-called quantum-cascade lasers in which the emission wavelengths are defined by engineering the subband energy separations in quantum well structures. The emission wavelength is therefore no longer determined or limited by the bandgap energy, making these lasers principally suitable for almost any operation wavelength in the mid- to far-infrared spectral region. With the wavelength limitation being given by the largest possible direct bandgap energy of the heterostructure laser active region, usually GaN based, the entire wavelength range from approximately 330 nm to 200 μm can now be covered with semiconductor lasers, as illustrated in figure 1. Furthermore, extensive research is directed toward improving white and high-brightness LEDs. Here, performance is mainly determined by the availability of suitable high-bandgap emitters and/or advanced concepts with a large emission bandwidth for efficient white light emission.

This focus issue presents many of the latest developments on semiconductor heterostructure research addressing optoelectronic emitters and other devices over the entire wavelength scale plotted in figure 1.

2. Lasers and LEDs for the short-wavelength visible and ultra-violet regions

In recent years, significant effort has been invested in the development of light emitters in the short-wavelength visible and ultra-violet regions, driven by numerous important applications with large volumes. The materials used at these wavelengths, such as GaN- and ZnO-based compounds and heterostructures, have a large bandgap and possess unique optical properties, such as a large excitonic binding energy. However, difficulties such as high dislocation densities due to a lack of suitable substrates, and insufficient electrical conductivities due to high dopant ionization energies (especially for the acceptors), represent considerable challenges for the development of high-performance emitters. Strong electric fields associated with piezoelectric effects and spontaneous polarization present additional challenges for the development of
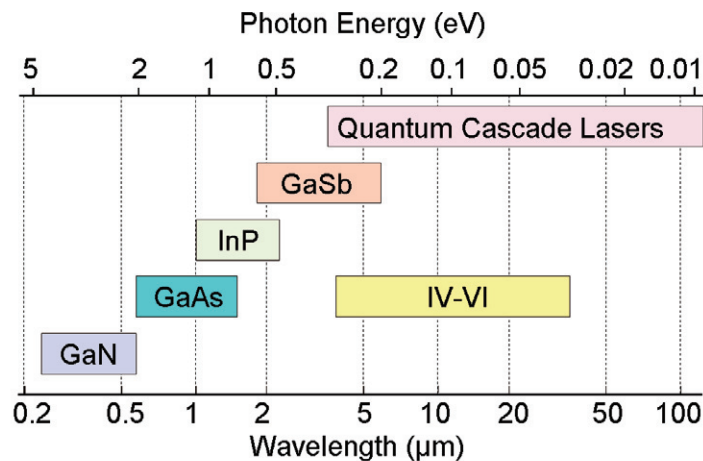
Figure 1. Material systems and wavelength coverages for heterostructure semiconductor lasers.

emitters in III-nitrides grown along a polar axis. Therefore, research in optoelectronics based on wide bandgap materials is still very much materials oriented.

Yoshida *et al* have developed a novel technique for epitaxial lateral overgrowth which enables the growth of low dislocation density AlGaN layers on sapphire. These templates have been used for the fabrication of AlGaN multiple quantum well lasers with relatively low threshold current densities at ultra-violet wavelengths as short as 336 nm. The results are presented in [1].

To circumvent the incompatibility between wide bandgap optoelectronic materials and available substrates, to allow for the use of a variety of substrates with different properties, and to enable the development of material structures with unique light emitting properties, nanoscale structures such as nanorods, nanowires and nanotubes are also under development. In [2], Willander *et al* present their work on ZnO nanorods grown on solid and soft substrate materials and demonstrate their potential for white light generation with excellent colour rendering. In [3], Hong *et al* report on the structural and optical properties of artificial arrays of GaN/ZnO coaxial nanotubes and demonstrate the overgrowth of InGaN quantum wells for light emission.

3. Near- and mid-infrared diode lasers

Semiconductor lasers in the near-infrared region around 0.8–2 μm are mostly based on GaAs- and InP-based heterostructure material systems. Major research has been directed toward the extension of the usual wavelength coverage, and toward growing heterostructures on other substrates, aiming for reduced costs and/or—in the case of silicon substrates—for integration with electronic circuits and other (passive) optoelectronic components. The former approach comprises the diluted nidride InGaAsN–GaAs–AlAs material system used by Guina *et al* [4] to realize high-power GaAs-based lasers around 1.2 μm; usable, for instance, for frequency-doubled yellow emission. The latter approach recently led to new types of hybrid silicon laser, suitable for optical interconnects, as presented by Dai *et al* [5].

The wavelength ranges 2–3 and 3–5 μm, on the other hand, are preferentially covered by GaSb-based band–band and interband cascade lasers exploiting the type-II heterostructure

alignment possible in the antimonides. While edge emitters have already been presented in the entire 2–3 μm wavelength range, Bachmann *et al* [6] demonstrate the recent breakthrough in electrically pumped vertical-cavity surface-emitting lasers at 2.3–2.6 μm wavelength, that operate in a single mode and can continuously be tuned by some 10 nm. Finally, Vurgaftman *et al* [7] show the impressive progress made on interband cascade lasers for the mid-infrared spectral range from approximately 3.2 to 5 μm, showing continuous-wave (cw) operation at, and even slightly above, room temperature for emission around 3.7 μm.

4. Mid- and far-infrared quantum-cascade lasers

Razeghi *et al* [8] discuss their most recent high-power quantum-cascade laser results at wavelengths around 4.8 and 10 μm. At 4.8 μm and room temperature record wall plug efficiency in excess of 20% and 16% is achieved in the pulsed and cw modes, respectively. Room temperature cw output power reaches 3.4 W. At $\lambda = 10 \, \mu$m, room temperature cw power of 0.62 W is obtained. The authors also explore lasers with photonic crystal distributed feedback, demonstrating up peak room temperature power levels in excess of 10 W and excellent beam quality.

Wang *et al* [9] report experimental demonstration of directional light emission from mid-ir quantum-cascade lasers with limaçon-shaped deformed resonators. These microcavities support high Q whispering-gallery-like modes, which lead to excellent in-plane directional emission with good optical power. The optimum range of deformation is investigated by simulation and experiment and the results are found to be in excellent agreement. While the measured spectra show a transition from whispering-gallery-like modes to a more complex mode structure at higher pumping currents, the far field is insensitive to the pumping current, demonstrating the predicted 'universal far-field behaviour' of this class of chaotic resonators.

Amanti *et al* [10] present a systematic study of a new terahertz quantum-cascade laser design that combines broad gain spectrum, high dynamic range and good high-temperature characteristics. It relies on a diagonal transition between a bound state and doublet of states tunnel coupled to the upper state of a phonon extraction stage. Low threshold current density and high slope efficiency make this device an attractive active region for the development of single mode quantum-cascade lasers. Single mode high power was achieved in continuous and pulsed wave operation.

5. Near-infrared intersubband devices

The large conduction band offset in quantum wells based on wide bandgap III-nitrides enables the development of optoelectronic devices based on intersubband transitions covering a large spectral range. In [11], Machhadani *et al.* discuss intersubband transitions in GaN/AlGaN quantum wells and show how the transition wavelength can be tailored to cover the entire spectral range from the near-infrared to the long-infrared. In particular they demonstrate waveguide modulators and quantum cascade detectors operating at the telecommunication wavelength of 1.55 μm.

6. Conclusion

Overall, this focus issue demonstrates that semiconductor lasers and other optoelectronic devices still constitute a rapidly evolving field almost 50 years after the first demonstration

of the pn junction laser in 1962 by three groups working at industrial laboratories (IBM and GE) and at MIT-Lincoln Laboratory. Short-wavelength (ultra-violet) and long-wavelength (far-infrared) semiconductor lasers, which only a few years ago were considered unrealistic, are now a reality, opening the door to new applications. We expect important advances in design, performance and applications to continue to be a dominant theme in the forthcoming decade.

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