europhysics news
BULLETIN OF THE EUROPEAN PHYSICAL SOCIETY

J.A. Volume 19 Number 1 January 1988

Semiconductor Lasers The Device Physicist's Playground

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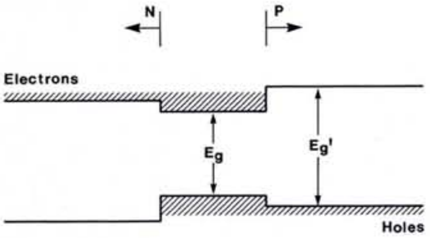
Lasing in semiconductors was first reported in 1962, shortly after the birth of other laser types, but some ideas in this direction can be traced back to a 1953 note by John von Neumann. This note has only now been published in its entirety, and appears together with a number of other papers on the history of semiconductor lasers in a special issue which also includes a large number of papers describing the latest achievements in this field [1].

It was only after the introduction of the double heterostructure concept (see next section) in the early 1970s that semiconductor lasers could operate continuously at room temperature, but since then the development has been fast, and it is now the laser type produced in the largest quantity. According to a recent survey [2] the sales in 1987 are expected to be over 10^7 units, exceeding HeNe lasers by more than a factor of 40 (HeNe again exceeds the total of all remaining laser types by about a factor of 10).

The success of the semiconductor lasers can be attributed to their many advantages over other laser systems, notably the following:

Fig. 1 — Band diagram of a double heterostructure under forward bias.



- small size, allowing very rugged and compact assemblies;
- they are electrically pumped and can be directly modulated up to very high frequencies;
- the conversion efficiency (output optical power compared to input electrical power) is high, over 50% has been reported;
- compatibility with fibre optics;
- very low cost;
- potential for integration with other optical or electronic function.

As a result of these advantages a wide variety of types are now manufactured. These range from very complex devices used in high data rate long range fibre optic communication systems to relatively simple mass produced and very cheap (a few $) devices used in consumer electronics, notably CD players. Development of very high power devices will make new applications possible; advances in material technology will mean that visible (600-700 nm) semiconductor lasers can be fabricated, which may eventually challenge HeNe lasers for many of the applications in which these currently dominate.

Fundamentals

Conventional contemporary semiconductor lasers have an active layer of low or undoped semiconducting material with a bandgap E_g sandwiched between a pair of n and p doped layers of material with a bandgap $E_g' \geq E_g$. When this structure is forward biased the band diagram is configured as in Fig. 1.

The exact band line-up depends on the materials used and is not even known precisely. The two heterojunctions form barriers preventing the electrons entering the p-layer and the holes entering the n-layer, thus confining the carriers to the active region, where they recombine. Looking at the active region we see that an 'inverted population' is formed, with a large number of electrons in the conduction band and a large number of holes in the valence band. This is the basis for lasing since, at a sufficiently high carrier concentration, stimulated recombination becomes dominant.

For most semiconductors, the refractive index is proportional to the inverse of the bandgap; consequently the double heterostructure also acts as a dielectric waveguide which, owing to the higher index of the active layer, confines the optical power.

GaAs/(GaAl)As forms a very convenient material system for semiconductor lasers since the bandgap can be increas-

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Published by the European Physical Society: 10 issues per year. *ISSN 0531-7479*

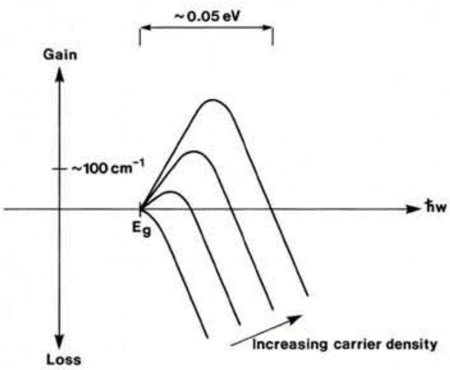

Fig. 2 — Gain/loss curves (highly schematic).

ed by increasing the Al content. A particular advantage of these materials is the fact that the lattice constant is almost independent of the Al content. This means that the various layers in the structure can be grown on a GaAs substrate with very little lattice mismatch, thereby maintaining a high material quality and hence device performance. The operating wavelength can be varied over the range 0.8-0.9 µm by varying the Al content in the active layer, with the restriction that the bandgap of the confinement layers must sufficiently exceed that of the active layer to prevent carriers leaking over the heterobarriers. It is GaAs/(GaAl)As lasers which are used in CD players.

Some of the particular features of semiconductor lasers such as their size, the possibility of direct modulation, and their inherent threshold behaviour (see next section), make these devices ideal sources for digital optical communication systems. For this application, wavelengths in the 1.3 and 1.55 µm regions are preferred owing to the dispersion and loss characteristics of optical fibres. These regions can be covered by using (GaIn)(AsP) compounds. The two degrees of freedom in the material composition allow selection of wavelengths in the 1.1 to 1.7 µm region as well as lattice matching to InP substrates. In practice a very large number of material compositions are possible using combinations of group III materials (Al,Ga,In) and group V materials (P,As,Sb). In addition lasing has been demonstrated in IV, VI compounds such as lead-salts and in II, VI materials.

Not all semiconducting materials are suitable for lasers, however, since at least the following conditions must be satisfied in order to fabricate lasers capable of continuous operation at room temperature:

(1) lattice matching to a suitable substrate,

(2) the structure must provide both carrier and optical confinement,

(3) the bandgap must be direct.

Gain in Semiconductors

The optical gain in the active region as a function of the carrier concentration can — at least in principle — be calculated from standard solid state physics theory. Examples of gain curves are shown in Fig. 2.

These gain curves show a number of remarkable features. We see that the gain values are very high, orders of magnitude above that for most other laser systems. Therefore the lasers can be very short typically $\cong 250\,\mu m$, and they do not need external mirrors; instead the necessary feedback can simply be provided by the Fresnel reflection from the cleaved facets which for a refractive index of around 3.5 gives a reflectivity, R, of $\cong 30\%$. The required net length gain g in the laser is found from the round trip condition $R \exp(gL) = 1$ where L is the length, giving $g \cong 50\ \mathrm{cm}^{-1}$ for $L = 250$ µm. The overall geometry of a semiconductor laser is shown in Fig. 3.

Lasing starts when the current supplied to the laser results in a carrier density which gives the necessary net gain. For higher currents the carrier density remains constant and all the extra carriers are subject to stimulated recombination.

A second feature of the gain curves is their remarkably large spectral width. This is due to the fact that we are dealing with transitions between energy bands (*cf* the conduction band and valence bands of the active layer) rather than transitions between atomic or molecular

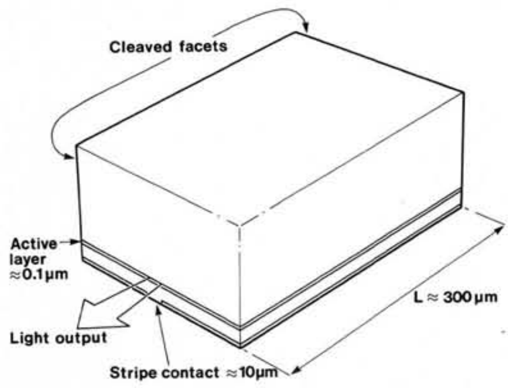

Fig. 3 — Schematic diagram of a semiconductor laser mounted with the active layer closest to the heat sink. For more details see Fig. 4.

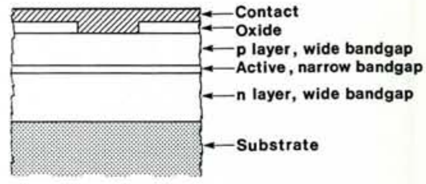

Fig. 4(a) — Simple oxide stripe laser.

states of well defined energy. As a consequence the lasers often operate in a number of different modes.

Semiconductors are transparent for photons with energies lower than that corresponding to the bandgap E_g, but highly absorbing for photon energies above E_g (see Fig. 2). The gain curves are therefore highly asymmetric. This is in contrast to other lasing materials where the gain curves can be described by a simple Lorenzian. It follows from the Kramers-Kronig relations that presence of gain (*i.e.* the imaginary part of the complex refractive index) leads to a modification of the real part of the index for photon energies in the vicinity of the gain peak. For a symmetrical Lorenzian gain curve, one finds that the change in the real part of the index is zero for the photon energy which has maximum gain. This is not the case for an asymmetrical gain curve and for a semiconductor it turns out that an *increase* in the carrier concentration (leading to higher gain) will result in a *decrease* of the real part of the index. This seemingly minor departure from conventional laser materials turns out to be very significant for a number of laser properties such as waveguiding linewidth, noise and behaviour under external feedback [3].

Laser Structures

From the gain curves, the recombination rates and the typical laser dimensions one finds that the current density required to reach the lasing threshold is of the order 1 kA/cm^2. Hence a laser simply consisting of a sandwich structure with a wide (*i.e.* several 100 µm) active layer in the middle will have a rather high threshold current because of the large area. Consequently thermal problems will prevent continuous operation. The obvious solution to this problem initially implemented was to restrict the current to a narrow stripe as shown in Fig. 4a.

Under forward bias, electrons and holes are injected into the active region.

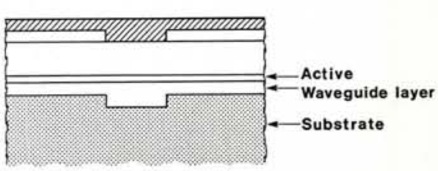

Fig. 4(b) — Laser with built-in waveguide.

Owing to carrier diffusion, the carrier concentration will taper beyond the edges of the stripe in this structure and carriers will be present over a region wider than the stripe. Since not only the gain but also the real part of the refractive index depend on the carrier concentration, the optical guiding properties in the junction plane are complicated and the quality of the output beam can be rather poor. Some form of built-in guiding is necessary to alleviate this problem. One possibility is shown in Fig. 4b where a guiding layer with a bandgap, and therefore also a refractive index, between that of the active layer and that of the passive layers is inserted. This creates a dielectric waveguide giving optical confinement in both the vertical and the horizontal direction. These structures still have the problem that a relatively large number of carriers must be supplied since some of them are diffusing away from the centre and do not contribute to the lasing process. The next step is therefore to create a structure where the active region is completely surrounded by high bandgap — low refractive index material thereby giving complete confinement for both charge carriers and photons. Such structures (for example Fig. 4c) usually require a two step growth procedure where some processing is necessary between the growth steps. Many of the advanced structures make use of the specific characteristics of growth over nonplanar surfaces.

The purpose of the layer structure shown in Fig. 4c is to block current outside the active region. However, various leakage paths exist and the p-n-p-n structure may also show thyristor behaviour. Details of the electrical properties can be modelled by constructing equivalent circuits for the structure, replacing the various junctions by diodes and transistors.

A very large number of laser structures in addition to those shown in Fig. 4 have been described in the literature.

Laser Dynamics

Carriers supplied to the active region either recombine non-radiatively by spontaneous recombination — giving rise to emission of light over a wide wavelength range — or they are subject to stimulated recombination, *i.e.* lasing. The photon population is fed by the stimulated recombination process and under DC bias, photons are 'lost' from the end facets at a constant rate.

The dynamic properties of semiconductor lasers are modelled by a set of rate equations describing the rate of change in the carrier and photon densities. In the simplest form this gives two ordinary, coupled, non-linear differential equations which give a quite good description of the laser transients and modulation properties. A more precise modelling of the simple structures (Fig. 4a and 4b) takes varying carrier and photon densities across the active region into account. This becomes particularly complicated for lasers without lateral optical confinement, since the optical guiding will depend on the carrier density which in turn depends on the lateral variation of the stimulated recombination.

It is normally assumed that semiconductor lasers are homogeneously broadened which means that all the carriers are available to the lasing process, *i.e.* the energy distribution of the carriers is neglected. This assumption, which predicts single mode operation, is valid if the energy relaxation time of the carriers is sufficiently short. While this seems to give a good description for GaAs/(GaAl)-As lasers the validity is more doubtful for the (GaIn)(AsP)/InP system. High frequency, high power, spectral and dynamic properties indicate that there is some degree of spectral hole-burning,

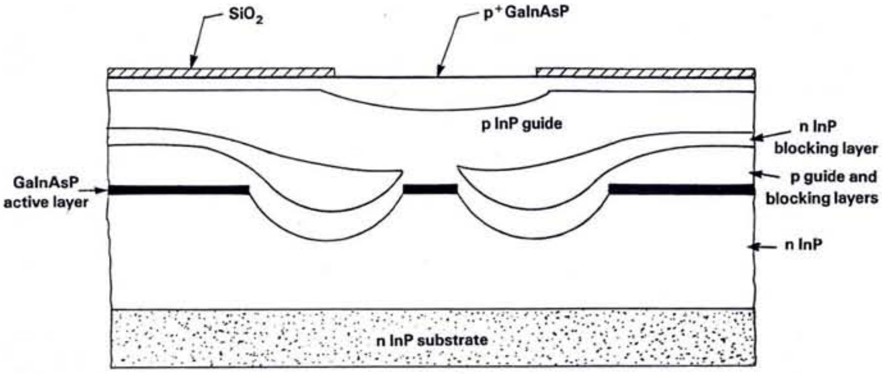

Fig. 4(c) — Double channel planar buried heterostructure laser (DCPBH).

i.e. inhomogeneous broadening. While there are good phenomenological models, the issue is still not satisfactorily settled.

Today any respectable field of physics dealing with dynamic systems is expected to produce examples of chaotic behaviour and other exotic phenomena, this of course also applies to semiconductor lasers. Examples include chaos and period doubling of modulated lasers, due to the interaction of the modulation and an internal photon — carrier density resonance, optical bistability of various structures, pulsations under DC bias due to unstable waveguiding, *etc.*

Improving the Spectrum

Semiconductor lasers usually emit light in several longitudinal modes spaced by 3 to 10 Å, the exact number depending on material, wavelength and device length. For fibre optical communication systems operating at high data rates, this may lead to problems since light of different wavelengths travels at different velocities owing to dispersion in the fibre. Consequently light from different modes arrives at different times, and after a long transmission length, the original signal can be lost. A particularly troublesome phenomenon is that of 'partition noise' which occurs because the spectral content changes from pulse to pulse.

Various methods for restricting the spectrum to one mode are being vigorously pursued, one noticeable example being the distributed feedback laser (DFB for short) which incorporates a periodic grating. The period of this grating is a multiple of a half wavelength thereby favouring the wavelength for which the reflections from the grating are in plane.

The width of an individual laser mode is typically in the 10-100 MHz range and the coherence length is relatively short. Recently the possibility of using semiconductor lasers for coherent fibre optic communication has received considerable attention since such systems could operate with power levels at the detector up to 20 dB lower than conventional systems. Line narrowing is therefore of interest since a linewidth of around 10^{-3} times the data rate is required for the most sensitive of the coherent systems. One possible method for line narrowing is the use of some form of an external cavity which leads to an increase of the stored energy and hence the Q factor of the laser.

Coherent systems also point to another desirable feature — namely tunability. By having a tunable local oscillator, systems akin to a conventional radio where the receiver can be tuned to one of a large number of channels become possible. The coherent receiver provides a spectral selectivity determined by the intermediate frequency amplifier. This gives the potential for hundreds of high datarate channels within a spectral range of a new nm, all transmitted on a single optical fibre.

Quantum Wells and Superlattices

New growth technologies such as molecular beam epitaxy (MBE) and metal organic chemical vapour deposition (MOCVD) have made it possible to grow extremely thin ($\leq$ 100 Å) layers. For such thin layers the carriers cannot move freely perpendicular to the layer, but are restricted to a number of well defined states. This resembles the well known particle-in-a-box problem, hence the name quantum well, or alternatively two dimensional system.

Use of quantum wells in laser structures leads to interesting phenomena. The lasing wavelength will depend on the active layer thickness since the possible states depend on the width of the quantum well. In addition it turns out that both the dynamic and some of the spectral properties are changed. These changes may be enhanced by a further reduction in dimensionality, leading to 'quantum wires' or 'quantum dots'. In the latter case the energy levels are discrete, looking more like an atomic or molecular system.

Other interesting possibilities include the use of superlattices, consisting of alternate thin layers of different materials. By using very thin layers, materials with different lattice constant can be grown on top of each other. The strain which would normally lead to defect is taken up by the superlattice. Use of strained superlattices therefore makes it possible to combine otherwise incompatible materials; one noticeable example is the growth of GaAs on Si. This has obvious microelectronic/optoelectronic implications. Another interesting subject is the modification of the valence band structure (lifting the light and heavy hole degeneracy) which may lead to lasers with much reduced threshold currents.

Outlook

Two topics which could become significant in the future are:

Integration: Semiconductors lasers can be integrated with other electronic or optoelectronic components thereby allowing more complex tasks to be performed by a single optoelectronic circuit. One specific application would be optical interconnection, allowing optical inter and intra chip communication, thus bypassing the electrical interconnection problems which are increasing with the increased size and complexity of electronic chips. For this application a low threshold current is important and recently values below 1mA were reported. Another interesting possibility is an integrated, tunable laser for coherent receivers. An important issue is the laser facets since integration is only feasible if laser facets can be made by methods other than cleaving, for example using etching processes.

Optical satellite communication: As more and more powerful lasers are being developed the possibility of optical communication between satellites is receiving increased attention. The specific features which make semiconductor lasers particularly attractive for this application are their small size and high conversion efficiency. An interesting possibility for high power lasers is the use of laser arrays where several lasing stripes are placed in close proximity. Ideally the stripes are optically coupled and consequently the array emits light in a single lobed narrow beam.

Conclusion

A selection of the large number of topics involved in semiconductor lasers have been discussed showing the very wide range of physics and physical phenomena relating to semiconductor lasers, and the reader will realise that almost irrespective of his/her background, he/she might be able to contribute and it is to be hoped would find this field interesting. This topic area is still under rapid expansion and promises to remain so for a long time ahead.

Acknowledgement: The author would like to thank his colleagues at Plessey Research and Technology for helpful comments to the various versions of the manuscript.

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FURTHER READING

For a general introduction to lasers see for example Yariv A., *Quantum Electronics* (Wiley, New York) 1975.

For a comprehensive and detailed coverage of the basic properties of semiconductor lasers see Casey H.C. and Panish M.B., *Heterostructure Lasers* (Academic Press, Orlando) 1978.