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SCIENCE

Semiconductor Lasers

A new optical and infrared maser is versatile, compact, efficient, and magnetically tunable.

Benjamin Lax

The terms *laser* and *maser* are interchangeably used to describe new quantum electronic devices which generate coherent electromagnetic radiation from the microwave through the infrared and into the optical regions. The words have evolved as acronyms of the phrases "light amplification of stimulated emission of radiation" and "molecular amplification" of such emission. In this paper they are used alternatively throughout, although by usage it is now preferred to use *laser* to describe the devices in the infrared and optical regions and *maser* for those in the microwave and millimeter regions.

One of the most exciting and promising recent developments in quantum electronics is the gallium arsenide diode maser (*1*). Although this is the first successful semiconductor maser, it is by no means the only one that has been conceived or the only type that will be operating in the future. However, what makes it unique is its small size, its relative simplicity, and, above all, its high efficiency in converting electrical energy into infrared radiation. Finally, the ability to modulate the radiation output with relative ease at high frequencies makes this member of the maser family one of the most attractive for purposes of communication.

After the invention of the original microwave maser (*2*) in 1954, physicists who were working with semiconductors soon began dreaming about applying the maser principal to materials of this class. This was a radical idea, since the natural phenomena of absorption and emission of quanta in semiconductors occur in the infrared region of the spectrum.

One of the first suggestions was made by John von Neuman in a private communication to Nobel laureate John Bardeen in which he outlined the basic concepts of the operation of a junction diode not very dissimilar from that achieved recently. Another early pioneer in this field was Pierre Aigrain (*3*) of the Ecole Normale in Paris. He and his co-workers have been very active in trying to achieve maser action in germanium by a variety of schemes in which both electrical and optical excitation or pumping are utilized. Since 1957 a variety of semiconductor masers, such as the cyclotron resonance maser and the impurity-level and interband masers, have been studied theoretically and experimentally at the Lincoln Laboratory of Massachusetts Institute of Technology. In 1959, Zeiger carried out calculations involving impurity and interband transitions which indicated that, in principle, maser action in semiconductors was possible. He considered recombination, in a compensated semiconductor, between neighboring pairs of acceptors and donors to be a very promising system. During the first Quantum Electronics Conference, held in September 1959, many of these ideas were openly discussed for the first time, and some preliminary estimates for the operation of a cyclotron resonance maser and for inversion of impurity levels at low temperatures were considered (*4*). A year and a half later, at the second Quantum Electronics Conference, some preliminary experiments were reported by Basov (*5*) of the Lebedev Institute, Moscow, in which his group claimed to have observed negative photoconductivity in silicon at low-level optical excitation. Unsuccessful attempts to achieve optical excitation of an indirect-transition maser of germanium were also reported by several groups. The first encouraging sign, indicative of eventual success, was the discovery by Keyes and Quist (*6*) at Lincoln Laboratory in the spring of 1962 that gallium arsenide diodes at liquid nitrogen temperatures emit infrared radiation at unusually high efficiencies. It was immediately recognized that it would be possible to construct a maser of gallium arsenide. Independently, in a paper published in the *Physical Review* in September 1962, Dumke (*7*) also concluded that a direct-transition maser of gallium arsenide was the most promising candidate among the types proposed. It is therefore not surprising that, during the summer of 1962, three groups, at General Electric, I.B.M., and Lincoln Laboratory, began to construct such a maser (*1*). In the fall of 1962 all three groups reported successful operation, the General Electric group having achieved the initial success. In March of this year, at the last Quantum Electronics Conference, in Paris, five groups reported some very interesting data on injection lasers made of gallium arsenide. In addition to the three

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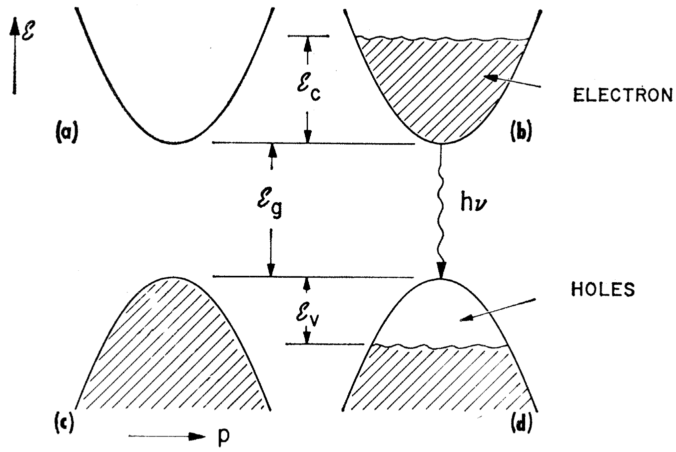


Fig. 1. Energy bands in a pure semiconductor at low temperatures; $\mathcal{E}$, energy; p, momentum; $\mathcal{E}_g$, the forbidden energy gap. (*a*) Empty conduction band; (*c*) full valence band. (*b*) Excited electrons fill the bottom of the conduction band; (*d*) the empty portion of the valence band contains holes excited into the band.

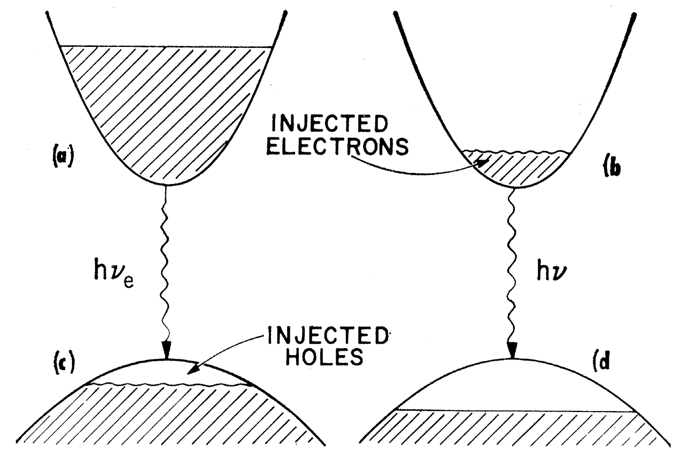


Fig. 2. Electrical injection of carriers to produce population inversion. (*a* and *c*) Holes are injected in a *n*-type semiconductor; conduction band (*a*) normally filled partially with electrons. (*b*) Electrons injected into the conduction band of a *p*-type semiconductor; (*d*) valence band normally filled with some holes.

original groups, whose work has now advanced fairly rapidly, the group from the Lebedev Institute in Moscow and another from Services Electronics Research Laboratory, Baldock, England, reported some experimental results. Today, in the United States, many laboratories have gallium arsenide masers in operation and are pursuing vigorous programs on the development of semiconductor lasers of this type.

Basic Principles

In operating any maser, one of the first requirements is inversion of the population of electrons which participate in the transitions resulting in the emission of photons. In a normal, pure semiconductor at low temperatures, the electrons are all in bound states in the valence band, as shown in Fig. 1 (*a* and *c*). However, if we suddenly apply a large electric pulse or a strong optical pulse of short duration, the electrons, on excitation, will enter the conduction band, leaving holes or vacancies in the valence band which become carriers of a positive electrical charge. These carriers come to equilibrium, as shown in Fig. 1 (*b* and *d*), in a period shorter than that required for recombination of the electrons with the holes. This new degenerate distribution no longer represents the lowest energy state of the electrons in the conduction band. Under these circumstances the electrons are said to be inverted. Then, as the electrons recombine with the holes, they drop from the conduction band to the empty states in the valence band, and for each such transition a photon of energy $h\nu > \mathcal{E}_g$ is emitted, where $\mathcal{E}_g$ is the energy gap of the semiconductor. It can be shown theoretically, and it may be inferred from Fig. 1, that the energy range of the photon emission can be expressed more properly (*8*) as

$$\mathcal{E}_g < h\nu < \mathcal{E}_g + \mathcal{E}_c + \mathcal{E}_v \quad (1)$$

where $\mathcal{E}_c$ and $\mathcal{E}_v$ are energies of the filled and empty portions of the conduction and valence bands, respectively.

Another pumping scheme, which is the one utilized in the junction diode lasers, involves electrical injection of minority carriers of holes or electrons across a *p-n* junction into either side which contains the appropriate impurities for making the normal conductions by electrons or holes, respectively. This is represented schematically in Fig. 2 (*a* and *c*), which shows an *n*-type semiconductor into which excess holes have been injected to create empty levels into which the electrons can cascade, with accompanying emission of a photon $h\nu$. Similarly, if the injection is into material of the *p*-type, which conducts an electrical current by holes and therefore contains empty states in the valence band, then the injection of excess electrons into the conduction band represents a departure from the equilibrium distribution and constitutes an inversion relative to the valance band. The recombination of the electrons and the holes in the valence band, in which the electrons make the transition from the upper state to the lower, results in the emission of a photon. In an actual junction it is not clear where the inversion occurs. It is very likely that it occurs right at the junction when the junction is biased in the forward direction. This bias results in the lowering of the energy bands, as indicated in Fig. 3, and the injected electrons and the holes overlap in the normally neutral "depletion layer" of the junction, approximating the situation represented in Fig. 1, thus creating a region of inversions, as shown.

The actual transitions of electrons really do not occur between the energy bands depicted in Figs. 1 and 2. These bands are represented for "pure" semiconductors. In order to create *n*-type or *p*-type materials, it is necessary to introduce impurities of the proper valence, which then create free electrons or free holes. At the same time, energy states are introduced into the forbidden region below the conduction band or above the valence band, indicated in Fig. 4, as the increased density of the energy states. In this case the energy of the emitted photon is less than that of the energy gap—that is, $h\nu < \mathcal{E}_g$. In the diode lasers, this is indeed the situation. Three mechanisms have been proposed to explain this. One possibility is a transition from a donor state to the valence band; the second is a transition from the conduction band to an acceptor state; and the third is a transition from a donor state to an acceptor state. Recent experiments provide support for the third mechanism. The evidence is circumstantial, but it suggests that the inversion occurs in the compensated region of the junction, where neighboring donor and acceptor impurities provide efficient recombination centers.

So far we have discussed the simplest type of transition which may give rise to the recombination and emission of photons—a transition which occurs when the valence and the conduction bands are located at the same momentum in the energy-momentum diagram. However, in semiconductors such as germanium and silicon, the valence-band maximum and the conduction-band minimum are displaced, as shown in Fig. 5. Thus, if an electron at the top of the valence band is to make a transition to the bottom of the conduction band at low temperature by absorbing a photon, the energy required will be

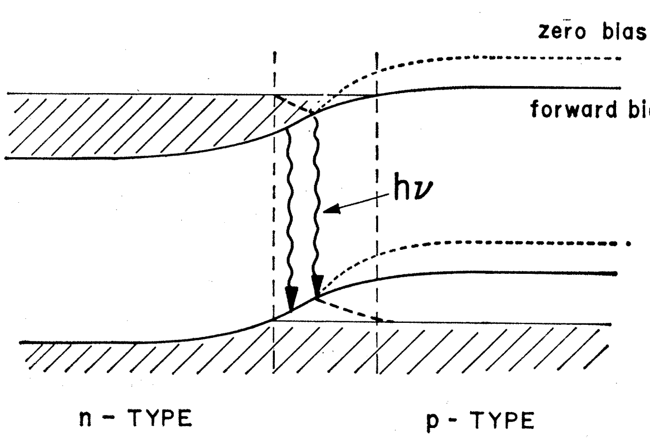
$$h\nu_a = \mathcal{E}_g + h\nu_p \qquad (2)$$

where $h\nu_a$ is the photon energy absorbed and $h\nu_p$ is the energy of a phonon created. This means that the electron, in order to alter its momentum, must transfer this change of momentum to the lattice, exciting a vibrational mode called the phonon. According to the law of energy conservation, this energy must be supplied by the photon which excites the electron transition. However, when an electron makes a transition downward from the conduction band to the valence band, it also excites a phonon, and it must provide the necessary energy. Hence, the energy of the emitted photon is less than that of the energy gap by the energy of the phonon; that is,

$$h\nu_e = \mathcal{E}_g - h\nu_p \qquad (3)$$

Consequently, at low temperatures when electron-hole pairs are created in semiconductors like germanium and silicon, where an indirect transition is involved, they constitute a population inversion. This type of device is called a two-boson maser, since both a photon and a phonon obey Bose-Einstein statistics and are called bosons. Since the indirect transition involves a phonon in addition to a photon, it is a second-order process and therefore has a lower probability and is less efficient than the direct process discussed earlier, which involves only a photon. In pure materials at very low temperatures, coulomb attraction between the hole-electron pairs forms a hydrogen-like structure called the exciton. Since the pair moves through a lattice with the momentum of the electron, the energy is represented as a band below the conduction band in Fig. 5. At very low temperatures the exciton transition shows up as an enhanced absorption and emission over a narrow region of energy below the energy gap. Another scheme for increasing the emission of radiation in an indirect transition is illustrated in Fig. 4. In this scheme, impurities can introduce a peaking of energy states below the conduction band or above the valence band, or both below the one and above the other.

The use of compensated material appears to be the most promising approach, from the standpoint of theory. However, various attempts to operate the two-boson maser have been made without success. The most extensive effort has been that made by Benoit à la Guillaume at the Ecole Normale, who has tried to inject hole-electrons



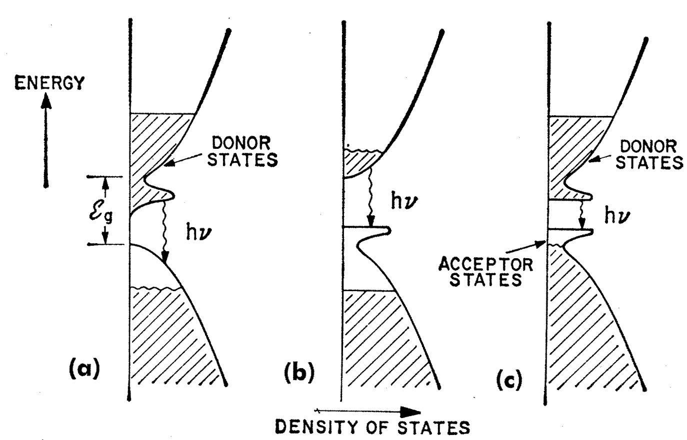
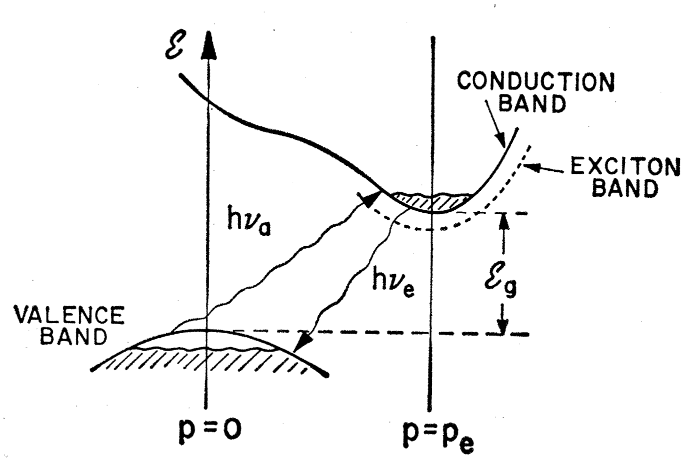


Fig. 3 (above left). Population inversion and photon emission at the *p-n* junction of a diode, through application of forward-biasing voltage, which lowers bands on the *p*-side relative to the *n*-side. (Dotted line) Normal diode; (solid line) diode with applied voltage.

Fig. 4 (above right). Density of energy states. (*a*) *N*-type material containing donors; (*b*) *p*-type material with acceptors; (*c*) compensated material with donors and acceptors. (For highly doped degenerate material the protruding impurity levels spread and merge into the bands as a continuum.)

Fig. 5 (right). Indirect transitions in semiconductors: $h\nu_a$, energy of absorbed photon; $h\nu_e$, emitted photon; $h\nu_a > h\nu_e$.



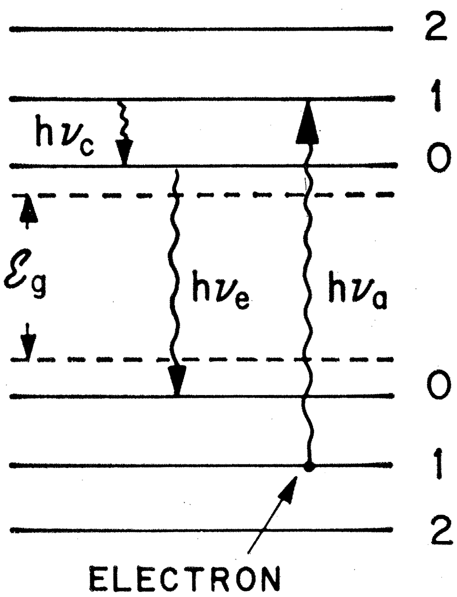


Fig. 6. Energy levels of a semiconductor in a magnetic field; $\mathcal{E}_g$, energy gap at zero field.

pairs into the intrinsic or *i*-region of a *p-i-n* structure in germanium. Optical pumping in pure germanium and silicon has also been tried without avail. Although, theoretically, the indirect-transition maser is less promising than the direct-transition type, nevertheless, with a favorable degree of excitation and impurity concentration, development of an indirect-transition maser appears possible.

Magneto-optical Masers

When a semiconductor is placed in a magnetic field, the properties of the energy bands are modified in such a manner that new phenomena, suitable for applications to the problem of developing new types of masers, occur. For the interband masers we have been discussing, the magnetic field offers the possibility of tuning, since the energy levels become quantized in the coordinates perpendicular to the magnetic field. The energy levels in the conduction and valence bands, when the coordinate along the magnetic field is neglected, are represented by

$$\begin{aligned} \mathcal{E}_c &= \mathcal{E}_g + (n + \tfrac{1}{2})\, h\nu_c \\ \mathcal{E}_v &= -(n + \tfrac{1}{2})\, h\nu_v \end{aligned} \tag{4}$$

where n is a quantum number and ν_c and ν_v are the cyclotron frequencies of the electrons and the holes, respectively, which are given by the equation ν_c, $\nu_v = eH/2\pi m_{c,v}c$; here e is the electron charge, H is the magnetic field, m_c and m_v are the electron and hole masses, and c is the velocity of light. As the magnetic field is increased, the energy gap increases by an amount $\Delta \mathcal{E}_g = \tfrac{1}{2}h(\nu_c + \nu_v)$. In materials such as indium antimonide and indium arsenide where the masses are very small, the energy gap increases by about 10 percent for a field of 100,000 gauss. With the fields available today, this increase can be easily extended by a factor of 3. In these materials, where impurities are involved, the tuning at high fields is about the same as for the interband transitions.

Another interesting application of the finding of quantized energy levels in coordinates perpendicular to the magnetic field is shown in Fig. 6, in which the operation of the optically pumped cyclotron resonance maser is shown schematically (see also *9*). A strong optical source, such as another junction diode or a diode maser, whose photon energy is somewhat higher than that of the energy gap of material in the magnetic field, is used to excite electrons selectively from level 1 of the valence band to level 1 of the conduction band. Hence, in a maser structure resonant at the cyclotron frequency, the electrons are stimulated to make transitions downward and emit photons at the cyclotron frequency. This can occur at wavelengths from about 10 microns in the infrared to 100 microns or more in the far infrared. Figure 6 also shows the interband transition downward between the 0 levels. This interband transition is desirable and necessary for continuous operation of the cyclotron resonance maser. I have described optical pumping of this maser, but electrical injection in diodes is also possible. This would of course involve interband transitions of the type indicated in Fig. 7, in which the electrons may be injected across a *p-n* junction into the conduction band on the *p*-side. The diode then behaves like an interband maser, and its effectiveness increases with increase in the magnetic field. At the same time, the electrons which have thus made the transition from the magnetic sub-band 0 of the conduction band to sub-band 0 of the valence band are inverted relative to sub-band 1 of the valence band. Then cyclotron resonance transitions at frequency ν_c can be induced, to give a cyclotron resonance maser. Another scheme for electrical pumping of a cyclotron resonance maser is shown in Fig. 8, in which the energy diagram of a tunnel diode containing a high concentration of *n*-type and *p*-type impurities is depicted in a magnetic field. The energy bands on either side of the junction are displaced vertically because of the high concentration of impurities; hence application of a small voltage in the forward direction permits an electron from the *n*-side to tunnel across the forbidden energy gap into the empty states of the valence band on the *p*-side. The magnetic field is oriented parallel to the current, an orientation which allows it to make transitions between the two magnetic sub-bands 0. The 0 level of the valence band is thus inverted to level 1, an empty magnetic level of the valence band. Hence, in a resonant maser structure the electrons are induced downward to level 1 at the cyclotron frequency, to provide coherent radiation from a cyclotron resonance maser.

Once it has become possible to achieve population inversion of electrons in a higher energy state, the first requirement for the production of photons is fulfilled. The action for stimulating an avalanche of successive photons may be initiated spontaneously. Thus, one photon induces an electron

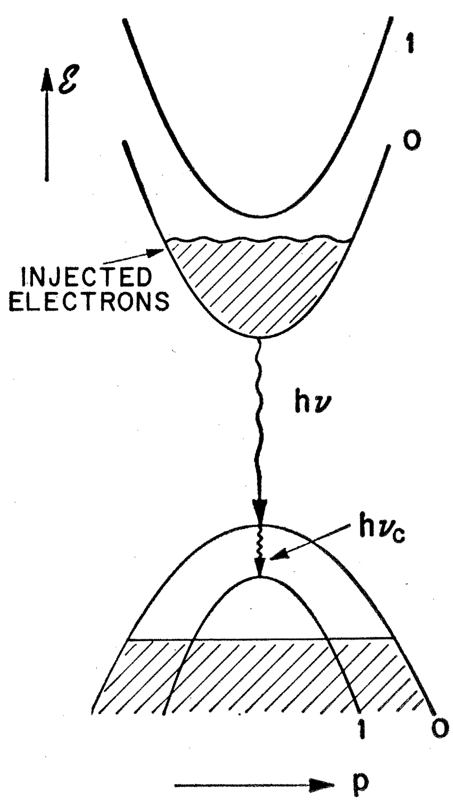
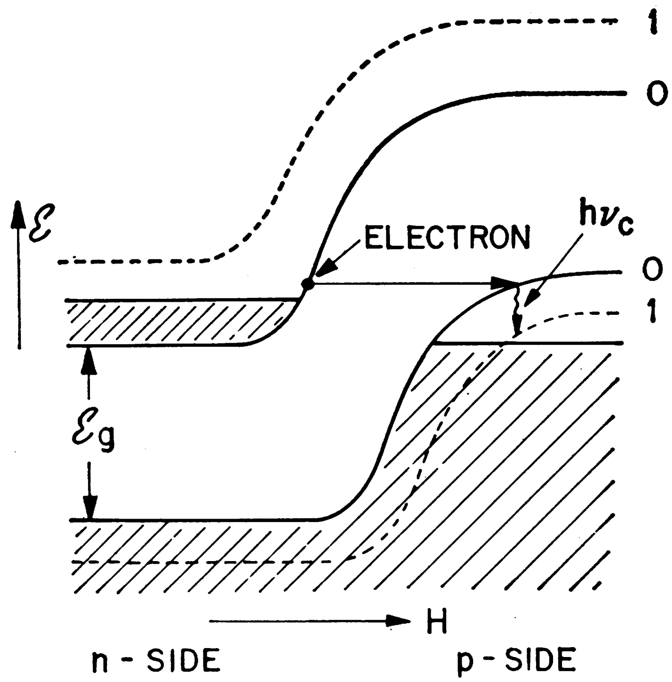


Fig. 7. Energy transition of an electron in an inverted *p*-type semiconductor in a magnetic field; $h\nu_c$, energy of emitted photon at cyclotron frequency.



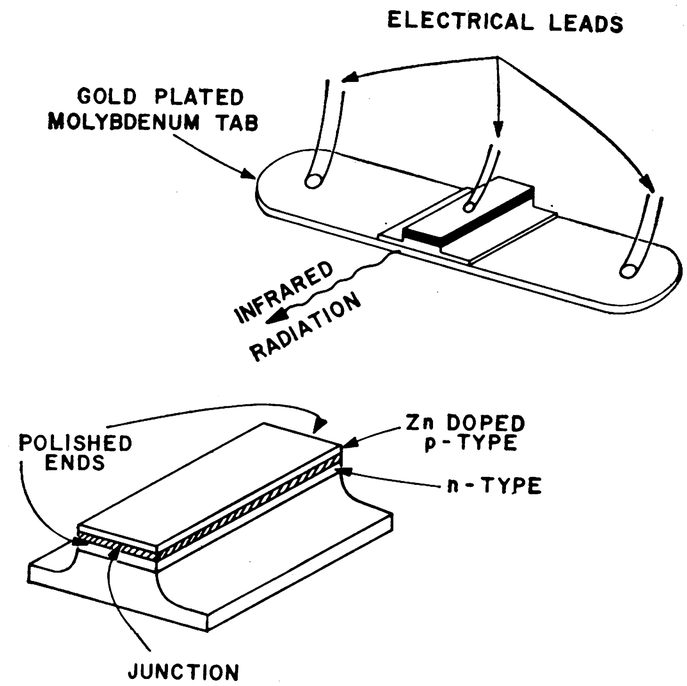


Fig. 8 (left). Energy diagram of a tunnel diode in a magnetic field. The electron tunnels electrically to the top of the valence band to level 0 and emits a photon of energy $h\nu_c$ at cyclotron frequency as it drops to level 1. Fig. 9 (right). Schematic drawing of the *p-n* junction in a gallium arsenide diode maser.

to make a transition from the higher to the lower state, with resultant emission of a second photon. This triggers a third, which produces a fourth, and so on. Each photon in this succession has a phase that is fixed relative to the phase of the preceding photon. In a resonant structure in which the wave thus produced is reflected, a coherent radiation pattern is established. Coherence, then, becomes a second requirement for a maser. The third requirement is that the maser be capable of operating as an amplifier or as an oscillator. For operation as an amplifier, it is necessary that the internal losses be overcome. For operation as an oscillator, the total losses of the system must be exceeded by the energy produced by the photon-creation process. These losses in a semiconductor laser may be divided into two main categories—bulk losses and surface losses. The bulk losses which are usually the most important, particularly at longer wavelengths, are those due to free carrier absorption. The presence of holes and electrons results in the transfer of energy from the photons to these carriers, and these in turn collide with the lattice, thereby giving up their energy, as heat, to the crystal. The surface losses may be threefold. (i) The radiation is usually only partially reflected at a polished face of a crystal under normal circumstances; the portion transmitted represents loss of photons which can no longer stimulate further emission. (ii) If the surface is rough, it will scatter some of the photons randomly, thereby disturbing the coherence; this scatter can be minimized by careful polishing of the reflecting surfaces. (iii) In the semiconductor laser of the junction type, even if the surface is a perfect reflector, not all of the reflected energy is directed into the narrow region of the active inverted layer of the junction, because of diffraction. At the surface of the semiconductor the coherent wave has a radiation pattern, both externally and internally, which has an angular distribution. Only those photons within a certain angle are effective. Fortunately, the radiation pattern is concentrated in a fairly sharp lobe, and thus the losses due to diffraction are not serious. The internal reflection and distribution of the electromagnetic

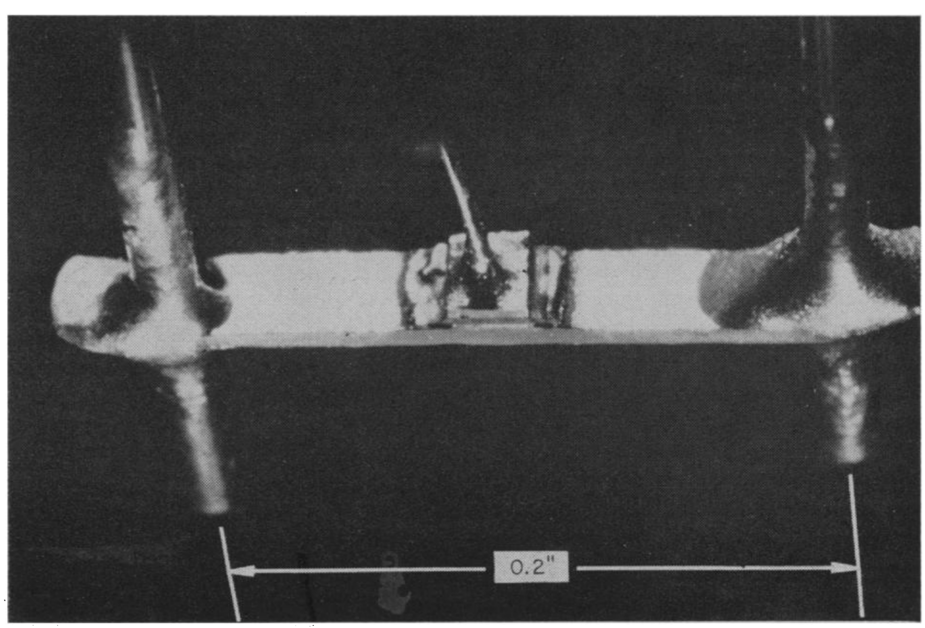


Fig. 10. Photograph of a gallium arsenide diode maser.

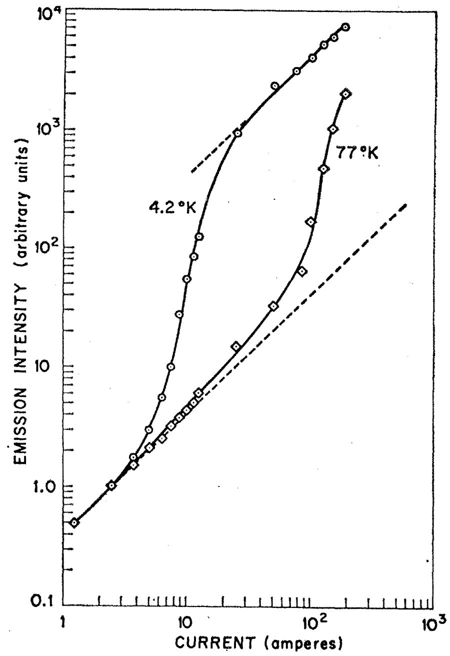


Fig. 11. Variation of radiation intensity with current in a gallium arsenide diode.

energy are accounted for by theory. Once all these losses are balanced by the photon energy created, the maser begins to operate as an oscillator. Any energy in excess of this threshold energy enhances the radiation output of the maser. One other source of energy loss in a diode maser is the ohmic series resistance loss in the bulk material on either side of the junction due to the high current. This loss limits the overall efficiency of the masers at present to about 30 percent.

For the direct-transition masers represented in Figs. 1–4, it can be shown theoretically that the energy created can easily overcome the losses. Since this is a first-order process, at appropriate levels of electrical or optical excitation the required inversion of carriers at a concentration of approximiately 10^{14} per cubic centimeter is readily achieved. In the indirect transition the situation is less favorable, because the inverted population has to be much larger, since the probability of recombination—a second-order process —is less than in direct transition. Hence, the energy created by stimulated emission has to overcome greater free-carrier losses in indirect transition. It is therefore not surprising that efforts to develop a practical two-boson maser have not yet met with success. To develop a maser of this type is just more difficult; it will probably require a higher level of excitation and more careful design.

Experimental Results

A diode for maser operation is usually prepared from a wafer of a gallium arsenide which may contain n-type impurities of the order of 10^{17} to 10^{18} per cubic centimeter. The wafers, usually rectangular in shape, are typically of the order of 0.5 to 1 millimeter, or even less, in length and width, and they are polished to a thickness of 0.1 millimeter. The diodes are alloyed to a tab of gold-tin plated molybdenum to form an electrical contact to the n-side, as shown in Fig. 9. A strip of silver-gold alloy is evaporated on the p-type surface to make the other electrical contact. The ends of the diode are cleaved or polished flat and parallel to form a reflecting Fabry-Perot interferometer. The coherent radiation emerges from these two polished faces, as indicated in Fig. 9. Figure 10 is a photograph of such a maser, with electrical leads to the molybdenum tab and one to the p-side of the junction.

For operation as a maser, the diode is usually immersed in a bath of liquid nitrogen at 77°K or a bath of liquid helium at 4.2°K. Relatively large current pulses of a few microseconds to a fraction of a microsecond, with a repetition rate varying from 10 to 1000 pulses per second for the shorter pulses, are applied to the diode. The radiation is then detected by a silicon photodiode, and the intensity of the radiation from the polished faces is measured as a function of current. As the peak current is increased to about 100 amperes at 77°K, the intensity begins to rise very rapidly; similarly, when the current exceeds about 6 amperes at 4.2°K there is a sharp rise of intensity, as shown in Fig. 11. The threshold for this anomalous behavior corresponds to current densities of approximately 10,000 amperes per square centimeter at 77°K and about 600 amperes per square centimeter at 4.2°K. When the radiation is monitored with a monochromator and the spectrum of the emitted radiation is studied as a function of radiation, a typical pattern, indicated in Fig. 12, appears. Above the threshold the emitted line narrows considerably from about 100 angstroms to less than 1 angstrom at 4.2°K. This is one indication of maser action. The spectrum of another diode was recorded photographically as it emerged from a high-resolution grating spectrometer (*10*) (Fig. 13). At 15 amperes, below the threshold, the line width of the

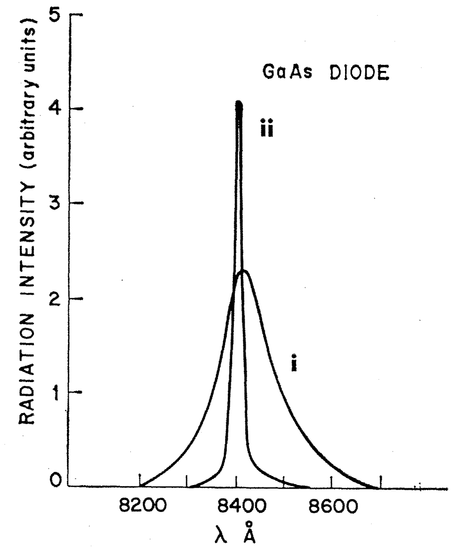


Fig. 12. Spectrum of radiation as a function of wavelength at 77°K in a typical gallium arsenide diode, (i) below threshold current, and (ii) above threshold current to operate as a maser.

spontaneous emission for the incoherent radiation exceeds the width of the film shown in the photograph. At 20 amperes, just above threshold for maser action, only a single narrow line, about 0.5 angstrom wide, appears. As the current is increased to 40 amperes, well above threshold, many other narrow lines appear. These correspond to other resonance modes of the Fabry-Perot interferometer and provide further evidence of the coherent nature of the emitted radiation. These emission lines are more dramatically illustrated in the densitometer trace of the spectra (Fig. 14). This trace also shows that the spacing between neighboring modes of the optical resonator is about 1 angstrom, a value which corresponds very closely to the approximate theoretical value for this spacing given by the equation $\Delta\lambda = \lambda^2/2n_0d$, where the wavelength, λ is 8400 angstroms; the length of the interferometer, d, is 1 millimeter; and the index of refraction, n_0, is 3.6.

Two other important properties of the gallium arsenide maser which have been investigated are the diffraction patterns and the radiation patterns in the horizontal plane (plane of the junction) and the vertical plane. The diffraction patterns are those expected from a slit which emits coherent radiation. In this context, a very striking interference pattern is obtained when a mirror is placed behind one polished face of a diode and a photographic film is placed in front of the other polished face (*11*) as shown in Fig. 15. The rings generated from the interference of the two sets of waves emerging from the opposite ends of the maser offer very impressive proof of the coherence of the radiation. Measurement of the radiation pattern from one end shows a main lobe in both the horizontal and the vertical planes, with beam widths of about 1 and 6 degrees, respectively, as indicated in Fig. 16. These lobes correspond to luminescent filaments about 10 microns high and 60 microns wide along the length of the diode. Not all of the luminescent area is optically active. It is estimated from theory that there is a region of inversion of about 1 micron in the vertical direction. However, the electromagnetic or photon field decays exponentially above and below the active region and is optically luminescent for an effective width of about 10 microns (Fig. 17). The theory indicates that the electromagnetic field of the photons is created as a growing wave along the plane of the active region and is guided or confined along this plane. The theory also indicates that the electromagnetic field can be polarized into one of two configurations in a manner analogous to polarization in a dielectric wave guide or a light pipe such as an optical fiber. Polarization experiments so far have been inconclusive and indicate that both modes are operating. From theory one can also predict the threshold criterion in terms of the properties of the semiconducting diode—that is, the free carrier conductivity, the width of the active region, and the current necessary for maser action.

Discussion

In the foregoing paragraphs I have discussed the physical and optical properties of the typical gallium arsenide diodes developed for low-temperature operation. A number of subsequent developments have extended the initial results and produced a variety of interesting data. One of the objectives was to modify the construction of the maser so that it would operate as a continuously rather than an intermittently pulsed diode (*12*). This was accomplished by reducing the dimensions of the diode to about 0.1 by 0.5 millimeter and by polishing all four sides of the diodes, with two sets flat and parallel to each other. This served to lower the threshold. In addition, it

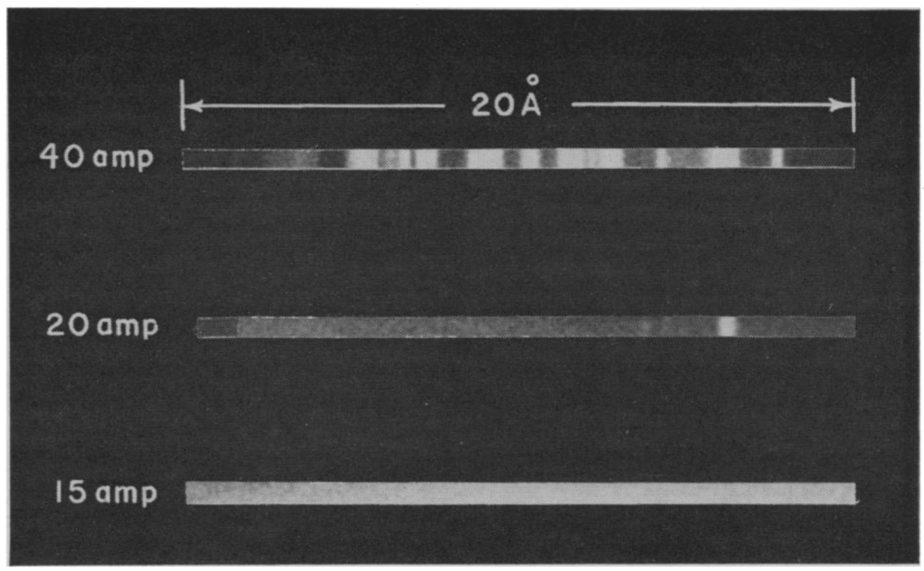


Fig. 13. Spectrum of a diode recorded on film. (Bottom) Below threshold, (middle) at threshold, and (top) well above threshold.

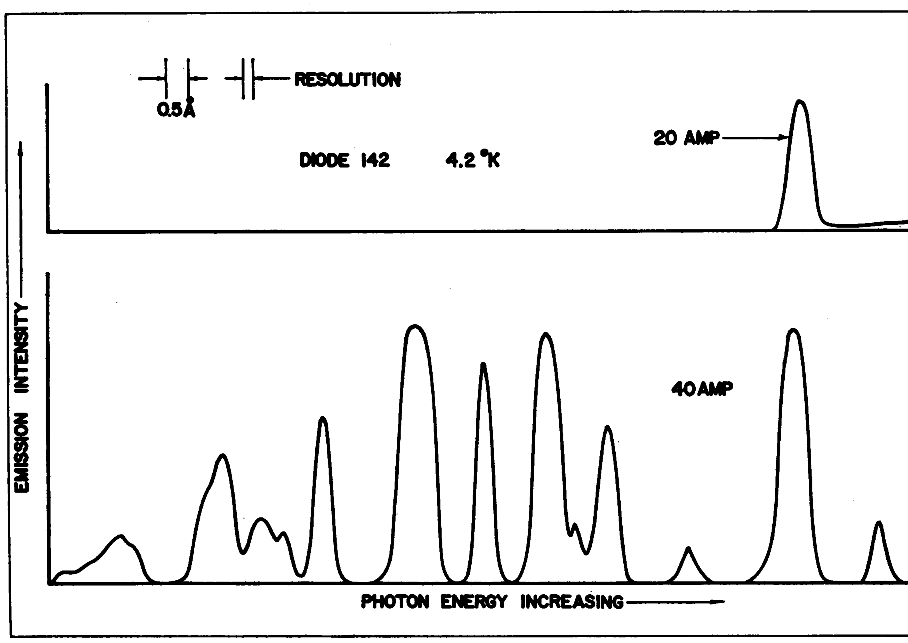


Fig. 14. Densitometer trace of the film of Fig. 13. The lower trace shows several resonance modes of the Fabry-Perot interferometer.

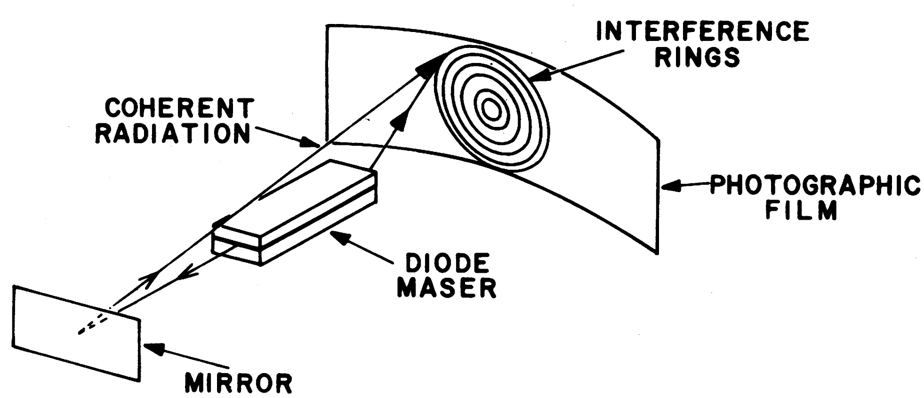


Fig. 15. Interference pattern of a gallium arsenide maser, showing interference of coherent radiation emerging from opposite polished faces of the diode.

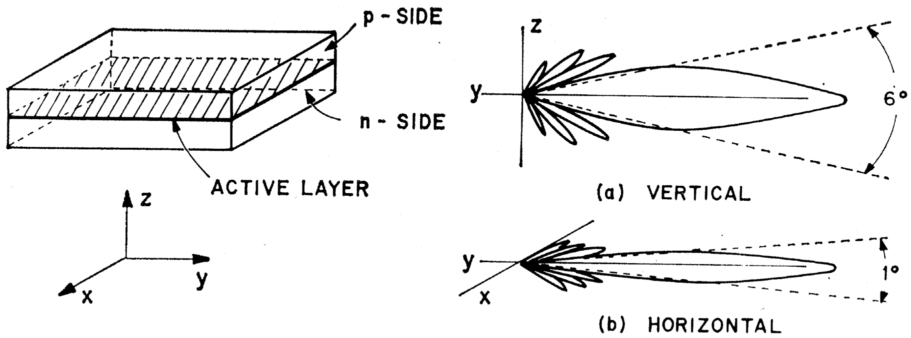


Fig. 16. Radiation pattern of a maser diode. (*a*) Vertical pattern with beam 6 degrees wide; (*b*) horizontal pattern with beam 1 degree wide.

is believed that the operating mode may have been such that the waves impinged on the sides at such an angle that reflection was wholly internal. This would have further reduced the threshold. Finally, by pumping the helium bath, the temperature of the diode was reduced to 2°K, and this also helped to lower the threshold. At 40 milliamperes of current—a value corresponding to about 100 amperes per square centimeter—continuous operation of the diode as a maser was achieved. The coherent radiation, which was about 10 percent of the total radiation emitted, was quite small, of the order of 10 milliwatts. This is smaller by several orders of magnitude than the peak power of the pulsed diode at 4.2°K, which produced about 280 watts, at an average power of about 30 milliwatts. Under more favorable conditions, with heat transfer facilitated through attaching the diode of two molybdenum blocks, on the *n*-side and *p*-side, respectively, an average power of 1 watt has been obtained at reduced peak values (*13*). Masers of improved structure have been operated at room temperature (*14*) with short pulses and low repetition rate, at a threshold of 100,000 amperes per square centimeter. Under optimum conditions the measured efficiencies of these diodes have been reported to be as high as 70 percent of the power across the junction, neglecting series losses. It is believed that the internal quantum efficiency is unity—that is, each electron crossing the junction gives rise to a photon.

An operating maser fabricated from an alloy of gallium arsenide phosphide ($GaAs_{1-x}P_x$) has also been reported (*15*). The radiation emitted exhibited line narrowing from 125 to 12 angstroms at 77°K at a threshold of about 20,000 amperes per square centimeter. The wavelength of the radiation for this material was in the red at 7100 angstroms. Probably it will ultimately be possible to make operating masers from other materials, such as indium arsenide (InAs) and indium antimonide (InSb), which have operated as incoherent diodes. Successful use of indium arsenide and indium antimonide would be of particular interest, since at low temperature these compounds emit radiation at 3 and 5 microns, respectively. Furthermore, it has been shown that they can be tuned by the magnetic field under the conditions established theoretically for relatively lightly doped diodes (*16*). Gallium antimonide (GaSb) has also operated as an incoherent diode, but as yet it has not been possible to attain maser action with this compound (*17*).

A number of unsolved problems still confront the physicist concerned with masers. One of these has been the controversy regarding the mechanism of the electron transition that gives rise to recombination and hence emission. There are five probable mechanisms. These involve, respectively, (i) the conduction band and an acceptor state; (ii) a donor and the valence band; (iii) an exciton and the valence band; (iv) an exciton and an acceptor; and (v) a donor and an acceptor. The last two seem the most likely candidates, since the Zeeman effect indicates a quadratic behavior with the introduction of a magnetic field (*18*), and this implies either a shallow exciton or a donor state just below the conduction band. From simple calculation of the photon energy and the value of the energy gap, we find that the terminal state must be above the valence band. This suggests that the acceptor states are involved. Another controversy involves the location of the inverted or active region. One school contends that this region is on the *p*-side of the junction. Another suggests that it is at the junction itself and probably straddles it, somewhat overlapping both the *p*-region and *n*-region, since the estimated width of 1 micron for the active region is greater than the width of the junction or depletion layer, which is about 1000 angstroms. A third controversy involves the nature of the trapping or guiding of the electromagnetic wave. One proposed mechanism is based on the view that there is a small dielectric discontinuity of the junction region and of the two layers containing free carriers on the *n*-side and *p*-side. A second is based on the view that the discontinuity is due to the inverted layer itself. According to theory, a guided mode with an exponential tail on either side would be created as a result of peaking of the electromagnetic energy by the generation of photons in the active region, independent of the change in dielectric properties due to the inverted electrons (*19*). The loss due to high concentration of holes and electrons merely

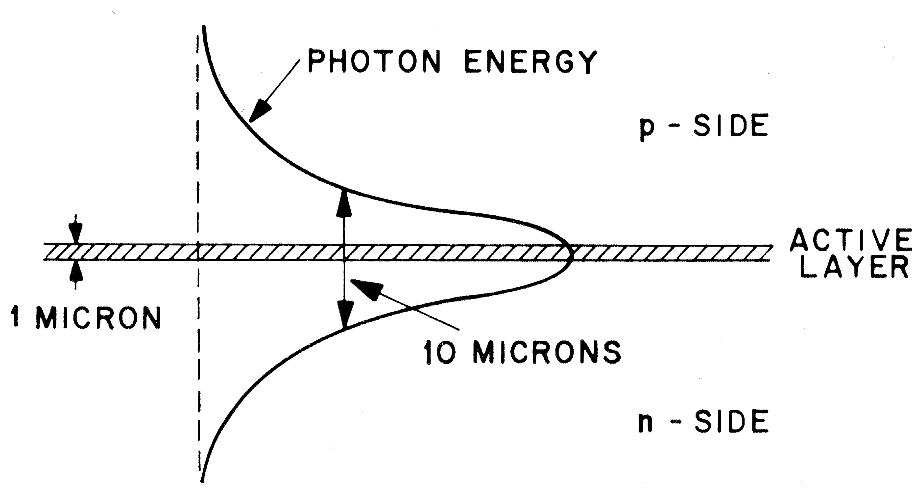


Fig. 17. Distribution of electromagnetic or photon energy above and below the active region of the diode maser.

makes the exponential tail drop more sharply on the sides. During maser action the wave is probably guided by the discontinuity of the inverted layer.

The invention of the semiconductor laser provides a new tool for applications and for scientific investigation. Although, at the moment, the peak power is small as compared to that of the ruby laser, nevertheless, some applications in this range are possible. It has been reported that a focused gallium arsenide maser beam has scorched paint from a surface. This suggests that some nonlinear phenomena in the infrared may be attainable with properly selected materials. At longer wavelengths, nonlinear effects of electrons in semiconductors will be observable even at presently attainable power levels. Of course, communication with semiconductor masers is definitely possible, since the incoherent diodes have already been utilized to transmit over a 30-mile link with power of a fraction of a watt (*20*). If the amplitude of the laser can be modulated at very high frequencies, the efficiency of the system will be greatly increased. The diode laser suggests that it may be possible to develop transistor-like devices in which the light, rather than electrons, actuates a collecting diode, with resultant amplification at very high frequencies (*21*).

Implicitly involved in all these applications is the search for a means of improving present lasers and of developing new ones of higher power. The possibility of designing semiconductor lasers for use at higher frequencies and, in particular, lower frequencies is under investigation. The use of alloys of semiconductors promises ultimate development of masers that will operate over a large range of wavelengths. It is apparent that, to achieve such advances, an extensive program is needed for producing pure crystals of compounds as well as crystals of compounds with known and controlled impurities. Such a program is necessary not only for developing the maser devices but also for making related basic investigations which will help to solve some of the puzzles involved. Such investigations will undoubtedly lead, in turn, to new discoveries and further applications.

Since this article was submitted for publication, a number of new developments have occurred which should be mentioned. Two new masers, one of indium arsenide (*22*) and another of indium phosphide (*23*), have been reported to emit infrared radiation at 3.2 microns and at 0.92 micron (9200 angstroms), respectively. The indium arsenide maser was made to operate continuously and tunable (*24*) by means of a magnetic field. In addition, a diode of an alloy of indium-gallium arsenide, $In_xGa_{1-x}As$, was made to emit coherently at about 2 microns (*25*), thereby demonstrating that coherent sources at wavelengths intermediate between 3.2 and 0.85 microns were attainable. Lastly, a gallium arsenide diode maser has been operated continuously with an output power of 1.5 watts at an overall efficiency of 30 percent including series losses in the diode (*26*). This represents the most powerful coherent source of infrared or optical radiation of any of the masers or lasers reported to date (*27*).

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