The Beginning of Integrated Optoelectronic Circuits

AMNON YARIV, FELLOW, IEEE

***Abstract*–The monolithic integration of electronic and optical functions on a single semiconductor crystal has become known as integrated optoelectronic circuits. These circuits usually contain a semiconductor laser and the associated driver electronics, detection and current amplication, or combine these two functions in an optical repeater. Monolithic integration leads to smaller circuits, greater ruggedness, and should result in lower cost.**

THE FOLLOWING is a descriptive summary of some of the main developments, as seen from my vantage point, in the field of *Semiconductor Integrated Optoelectronics.* By this name I mean to include the scientific and technological steps leading to the monolithic integration of electronic and optical functions on a single semiconductor crystal. This narration is a subset of the large body of work usually known as *Integrated Optics* that is concerned mostly with guiding and switching of light in electrooptic crystals such as $LiNbO_3$ and $LiTaO_3$ as well as in semiconductors.

Looking back I will choose as the beginning of my work in Integrated Optoelectronic Circuits (IOC), a research project back in 1963 at the Bell Telephone Laboratories in Murray Hill, NJ. A group of researchers consisting of Rogerio Leite, Walter Bond, Barry Cohen, and myself got together to look at GaAs semiconductor lasers. The latter had just been announced, more or less simultaneously, by three groups at the G.E. Research Laboratory, IBM, and Lincoln Laboratory, and it occurred to some of our wiser and elder superiors at Bell Laboratories that this new laser was potentially a useful device to A.T.&T. and that we had better get involved. The task of doing so was suggested to Rogerio Leite and me, probably because we were the new kids on the block and not yet deeply involved in any particular project. Barry Cohen fabricated the lasers (the model "A" diffused homojunction variety), Walter Bond designed and built the experimental apparatus, and Rogerio and I performed the measurements.

The main outcome of the investigation was the discovery of the existence of a dielectric waveguide straddling the p-n junction [1]. This fortuitous waveguide confined the laser light as it bounced back and forth between the cleaved facet mirrors and was responsible for the fact that the laser oscillation ensued. Without it, the high diffraction losses due to unguided propagation would have caused the threshold current to be unattainably high. This first experiment and the observed waveguiding are shown in Figs. 1 and 2.

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The author is with California Institute of Technology, Pasadena, CA 91125.

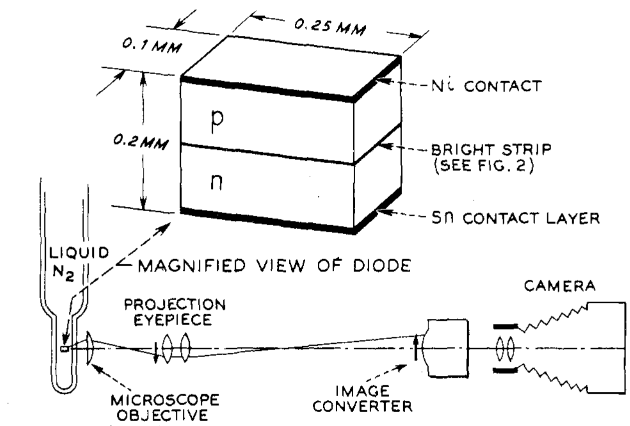

Fig. 1. The experimental setup for observing optical dielectric waveguiding in the junction region of a p-n GaAs diode [1].

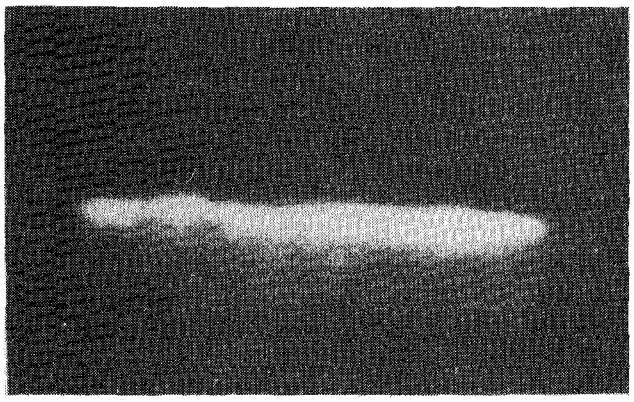

Fig. 2. A photograph of the front surface of the diode in which the bright region corresponds to light confined by the dielectric-waveguide effect [2].

The following year, in 1964, I joined the Electrical Engineering Department at Caltech and started setting up a laboratory in Quantum Electronics. The third student to join my group was David Hall, a first year physics graduate student.

In trying to think up a suitable research project, I remembered the old Bell experiments and suggested to Dave that the problem of dielectric waveguiding of light in semiconductors was of potential interest.

Instead of aiming for guiding in p-n junctions, as we had at Bell, we decided to have it take place in a surface waveguide which results when a high resistivity GaAs layer is grown epitaxially on a low resistivity substrate. The expected waveguiding in this case would be caused by a lowering of the dielectric constant in the low resistivity substrate relative to that of the surface layer by

$$\delta \epsilon = \frac{Ne^2}{m^* \omega^2} \tag{1}$$

where N is the carrier density in the high conductivity substrate and m^* is the effective mass of the carriers. It so happened that such structures were being fabricated at the time by researchers working on the Gunn effect and we hoped that some such device would fit our requirements.

David Hall spent the better part of two years looking for guiding in many crystal samples which were donated by various laboratories, with no success. Sometime toward the spring of 1969, we agreed that, if by the end of the summer we could not observe guiding, then David would abandon the experiment and move on to some "safe" project. Early that summer he went home to Hartford, CT, on vacation and there discovered a new, yet untapped by us, source of crystals at the United Aircraft Research Laboratories.

By the end of the summer Dave would process the crystals into appropriate samples and almost immediately, working with Elsa Garmire, who in the meantime joined us as a Post-Doctoral fellow, observed waveguiding. My own excitement was exceeded only by that of Dave to whom the bright strip of light on the image converter signified not only a successful experiment, but also a good part of his Ph.D. thesis.

Fig. 3 is a reproduction from the 1970 paper [2] describing the work. You will note that in addition to the waveguide, we also had a metal electrode on top of a crystal. This small but significant addition to the experiment made it possible to control the index of refraction in the guiding region by applying a (reverse) voltage between the substrate and the metal. The resulting depletion layer (Schottky barrier) electric field acting through the electrooptic effect of GaAs changes the dielectric constant of the guiding layer by

$$\delta \epsilon = \epsilon_0 n^4 r_{41} E \tag{2}$$

where r_{41} is the electrooptic coefficient of GaAs, n its refraction, and E the electric field.

The total change of the dielectric constant of the guiding channel $\delta \epsilon$ is thus the sum of (1) and (2) so that with a proper choice of the sign of E, $\delta \epsilon$ can be made to drop below the threshold value (for guiding) and the guiding would (and did) disappear. We thus had a voltage-controlled dielectric waveguide which could be used as a light modulator. This was the world's first surface guided-wave electrooptic modulator, a technique that, based mostly on $LiNbO_3$ as a crystal, would later become the mainstay for optical switching technology.

The next development in the field to impact our work was the publication in 1968 of an article by Shubert and Harris [3], then at the University of Washington, with the title of "Optical Surface Waves on Thin Films and their Applications to Integrated Data Processors." This paper was the first to suggest "... the applicability of thin films to optical data processing ... in which the thin film serves as the transmission medium ... and important elements are lenses, modulators and detectors," realized in thin film (i.e., dielectric waveguide) configuration. This paper was followed in 1969 by one written

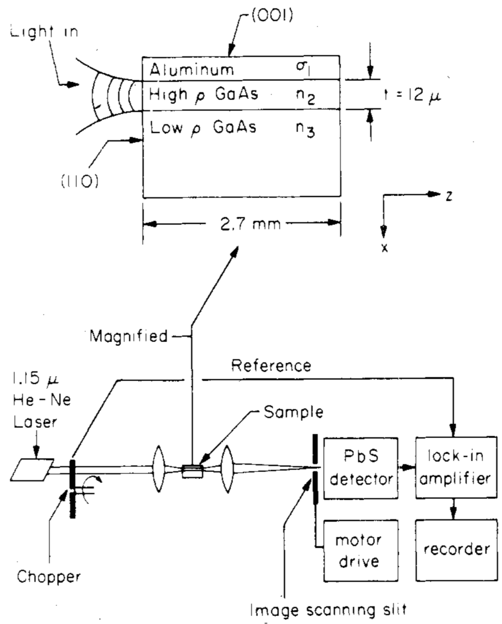

Fig. 3. (Upper) An epitaxial GaAs waveguide electrooptic modulator. (Lower) The experimental setup for observing the modulation [2].

by Miller in which thin film realization in glass of devices such as modulators, lasers, and resonators was suggested [4].

Reading the Shubert and Harris paper made me, for the first time, look beyond the narrow conceptual boundaries of our guiding and modulation experiment in GaAs. It dawned on me that GaAs was almost unique in the sense that it could "play" optical games (guiding), perform electrooptical modulation, detection, make excellent lasers, as well as act as a base material for purely electronic devices (metal-oxide field-effect transistors, Impatt, Gunn diodes, etc.). This meant that, in principle, we should be able to integrate any desired combination of these devices monolithically on a single substrate of GaAs. I described this possibility in the first Symposium devoted to this new field which was organized by R. L. Byer (Stanford) and O. Bryngdahl (XEROX, PARC) in Menlo Park, CA, in March 1971. To distinguish this field from its older brother—Integrated Optics—I referred to it as "Active Integrated Optics". Later that year in a meeting in Esfahan, Iran, organized by A. Javan, I came back to the same topic. I will take here the liberty of reproducing a few paragraphs from the proceedings of the 1971 conference [5] which deal with the issue of Integrated Optoelectronic Circuits.

> "... just as silicon and germanium have come to play a key role in integrated electronics, it is possible already to develop approximate criteria which point toward certain materials as candidates for active integrated optics applications. Some of the more important requisite properties are:
>
> 1) transparency and good optical quality for light in the visible and near-visible regions of the spectrum;
> 2) material should lend itself easily to interfacing with electronic circuits;
> 3) the material should be capable of light generation and detection;

4) the material should be capable of performing light switching and modulation functions. More specifically, it should possess large electrooptic and photoelastic figures of merit so that modulation and switching of light by either of these two techniques can be used;
5) the material should be suitable for thin-film dielectric waveguide fabrication.

There are many materials that can satisfy reasonably well one or two of these requirements and it is conceivable that future integrated circuits will combine a number of them for specific applications. It is interesting to note, however, that at least one class of known materials already comes close to fulfilling all of these requirements. This is the semiconductor GaAs and its related alloys, such as $Ga_{1-x}Al_xAs$ and $GaAs_{1-x}P_x$.

It may prove useful to go down our list of criteria and see how they apply, for example, to the GaAs alloy system.

1) GaAs single crystals have a (300 K) energy gap of 1.42 eV ($\sim 0.87\ \mu$) and have a useful transparency range of 1-12 μ. The energy gap and, hence, the optical cutoff frequency can be "pushed" into the visible in the Al or P alloys.
2) The ability to easily dope GaAs, to fabricate p-n junctions, and make ohmic contacts should prove useful in electrical interfacing. An example of such an application is described in Section VII.
3) GaAs is the material used most widely for injection semiconductor diodes. Such diodes emitting coherently (lasers) or incoherently (LED) can thus be built into the circuit. GaAs p-n junctions, reverse biased or unbiased (photovoltaic), can also be used for efficient light detection.
4) Both the electrooptic figure of merit [14] ($n_1^3 r_{41} = 6 \times 10^{-11}$ m/V and the photoelectric figure of merit [15] ($n^6 p^2/\rho v_s^3 \simeq 10^{-13}$) in GaAs are among the largest.
5) Epitaxial techniques for growing $Ga_{1-x}Al_xAs$ are well developed and have received a strong impetus because of their importance in the fields of solid state microwave oscillators and the heterojunction injection lasers [16]. The presence of a fraction x of aluminum causes the index to change by approximately

$$\Delta n \sim -0.4x$$

so that a simple dielectric waveguide can be fabricated by growing epitaxially a $Ga_{1-x}Al_xAs$ layer on a substrate containing a larger aluminum concentration. The techniques of epitaxy are easily adaptable to growing a large number of layers with different indices of refraction so that we can envisage bulk volumn integrated circuits stacked on top of each other and interconnected or coupled together. . . ."

With the above considerations in mind, we started in 1971 a systematic effort at Caltech to establish the feasibility of monolithic Integrated Optoelectronic Circuits (IOC). One of the first examples involved the integration of a Schottky barrier detector with a GaAs waveguide, as shown in Fig. 4. This was followed by studies of directional coupling and voltage-controlled directional coupling [6].

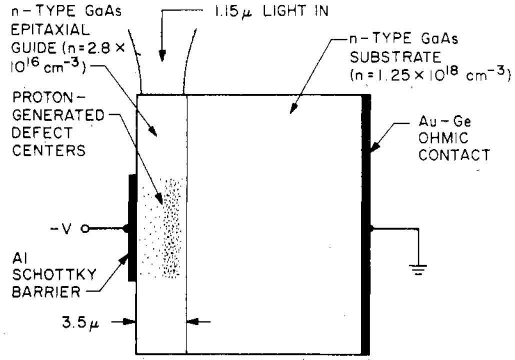

Fig. 4. An integrated GaAs epitaxial waveguide-detector combination.

The importance of GaAs based junction devices was also appreciated by Reinhart and Miller [7] at Bell Laboratories who demonstrated in 1972 phase modulators based on GaAs-$Ga_{1-x}Al_xAs$ double heterostructures.

At about this time it became clear to us that to make further progress in this field, we would need to be able to grow our GaAs-$Ga_xAl_{1-x}As$ structures. This, at the time, seemed to be a scary invasion into the black magic land of crystal growth. With the help of I. Samid, a Post-Doctoral fellow from Israel, and Elsa Garmire we set up two liquid phase epitaxial reactors and by 1972 were growing our own crystals. In retrospect, this was a crucial decision since the increasing complexity of the devices which were required made it all but impossible to get them from any other source but our own. It also pointed the way to the unavoidable need to develop at universities sophisticated semiconductor growth, fabrication and test facilities in order to perform meaningful research and train students in a new and technologically demanding area.

An integration of a different sort, that of a built-in filter and a laser involved the fabrication of semiconductor lasers with a built-in corrugation grating [8]. In these, so called, distributed feedback lasers, first proposed by Kogelnik and Shank [9], a built-in monolithic corrugated crystal layer [10] (Fig. 5) acts as a Bragg reflector which serves to couple the forward and backward laser beams, thus fixing the oscillation wavelength (at the Bragg value) while obviating the need for reflecting facets. Such lasers are now receiving renewed attention due to their promise for single frequency operation and a large number of commercial companies here and abroad are engaged in their manufacture.

A major impetus to our development of IOC's came when we started the fabrication of semiconductor lasers on semi-insulating substrates [11]. This made it possible for us to adopt a planar technology where all contacts are made on top of the wafer so that different devices could be interconnected electrically. An example of the first active device using this development was the integration of a Gunn diode oscillator and a laser diode [12], as shown in Fig. 6. The basic feature that makes this type of integration feasible is the layered epi-

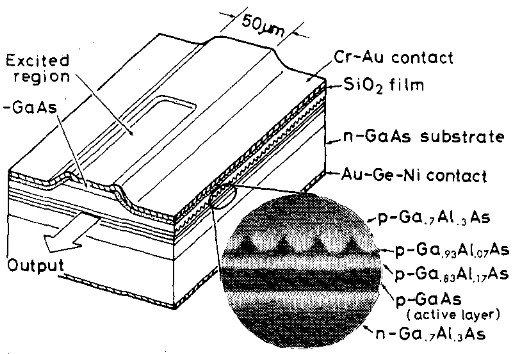

Fig. 5. A commercial grade GaAs/GaAlAs heterojunction laser with an internal built-in conjugation filter for wavelength stabilization (after [10]).

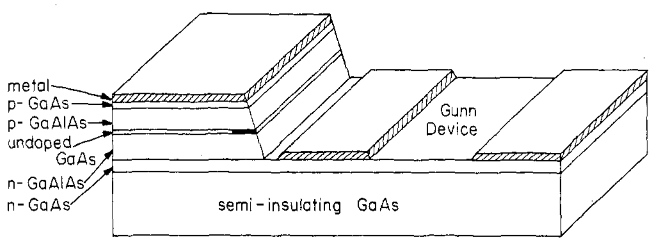

Fig. 6. A monolithic integration of a Gunn diode microwave oscillator with a laser diode (after [12]).

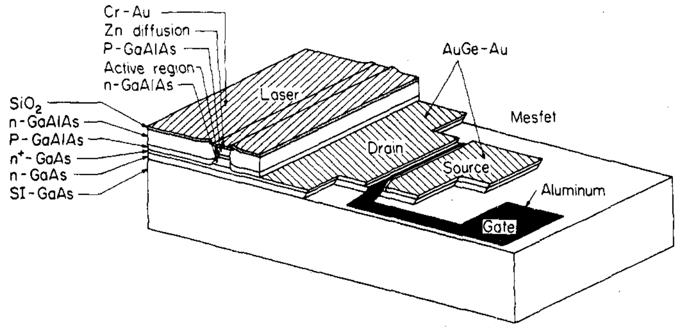

Fig. 7. A monolithic integration of a buried heterostructure GaAs/GaAlAs laser with a MESFET (after [16]).

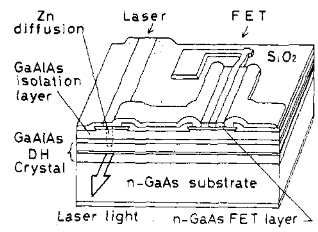

Fig. 8. Monolithic integration of a GaAlAs injection laser with a Schottky-gate field effect transistor (after [17]).

taxial structure common to both the laser and Gunn diode. We note in the figure that the GaAs(N) channel doubles as the active region of the Gunn diode as well as serving as the interconnect "wire" that carries the microwave current output of the Gunn diode into the laser, thus modulating the latter at the microwave frequency.

By 1974 there existed a number of laboratories which were pursuing semiconductor based integrated optoelectronics. An important development at Lincoln Laboratory [13] was a monolithically integrated $In_xGa_{1-x}As$ Schottky-barrier waveguide photodetector. At Bell Laboratories a p-i-n photodiode was integrated with FET [14]. At Caltech we concentrated our efforts on integrating a laser with a transistor driver. This combination was considered by us to be of generic importance since most of the applications envisaged for the semiconductor laser—be it in optical communication, printing, or optical logic switching—require that the laser be driven by a transistor source. By that time Dr. Shlomo Margalit, of the Technion in Haifa, Israel, joined our research group at Caltech, and with his semiconductor device wizardry raised considerably the sophistication of the devices we fabricated. Working together, I. Ury, then a graduate student and today the President of ORTEL Inc., Margalit, Yust and myself demonstrated in 1979 the first laser-transistor integration. This involved a GaAs/GaAlAs system [15]. A more advanced version [16] dating to 1982 is shown in Fig. 7. A group at Hitachi Research Laboratories in 1980 also integrated a FET with a laser [17], as shown in Fig. 8.

Fig. 9 shows the first functional integrated optoelectronic circuit. The circuit combines monolithically the basic functions of an optical repeater [18], namely: detection, current amplification, and a retransmitting laser which is driven by the amplified signal current.

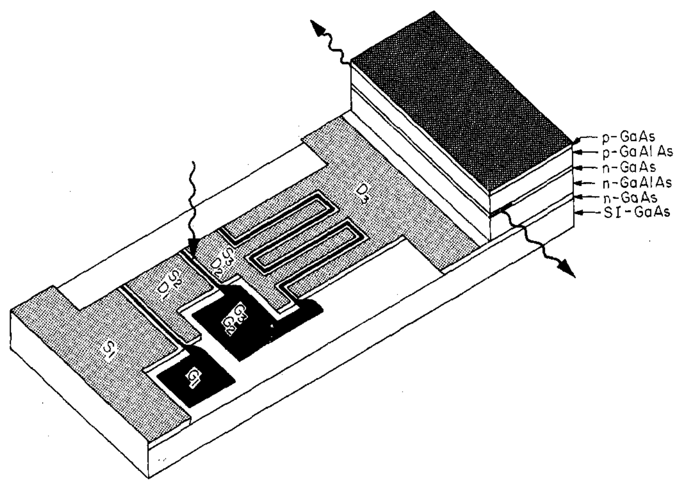

Fig. 9. An integrated GaAS/GaAlAs optical repeater consisting of three MESFET's and a laser (after [18]).

The field of integrated optoelectronic circuits has by now spread and is pursued vigorously in numerous laboratories. It is the subject of one of the national technical projects undertaken by a group of Japanese companies with the support of the Ministry of International Trade and Industry (MITI). One of the more complex IOC's produced to date is illustrated in Fig. 10. This comes from the Hitachi Laboratories and shows a circuit containing lasers and their associated electronics [19].

Since the early days of Integrated Optoelectronics, diode lasers which are based on the crystal system InP/GaInAsP have become important. This is due to the fact that the composition of these lasers can be chosen so they emit at $1.1\ \mu m < \lambda < 1.6\ \mu m$ which coincides with the low-loss region of optical fibers. The first laser-transistor integration in this system was demonstrated at Caltech in 1981 [20] and is shown in Fig. 11.

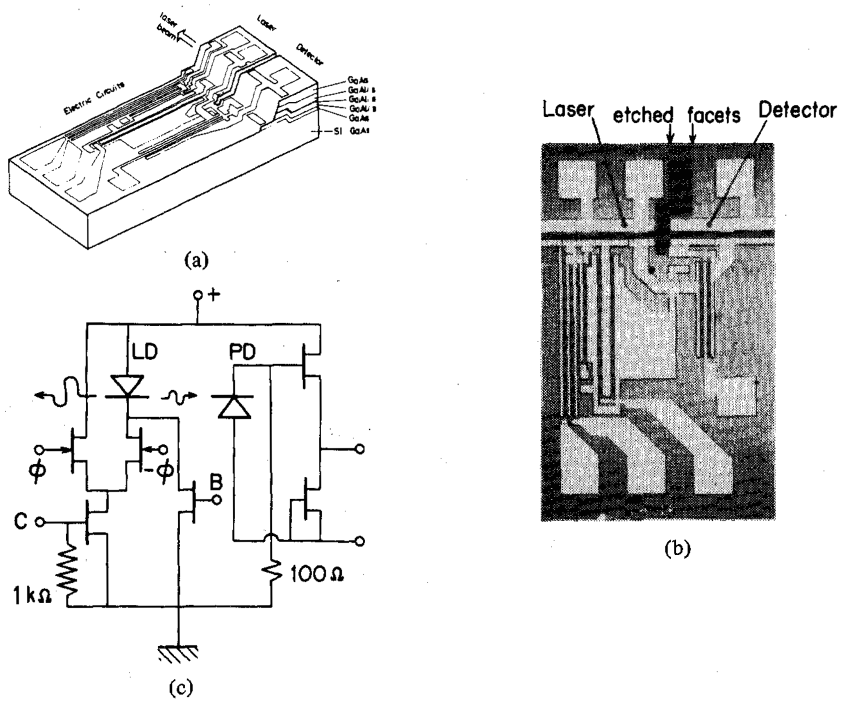

Fig. 10. An integrated optoelectronic circuit consisting of a laser, detector, and control circuits (after [19]). (a) Overall structure. (b) Photograph. (c) Circuit diagram.

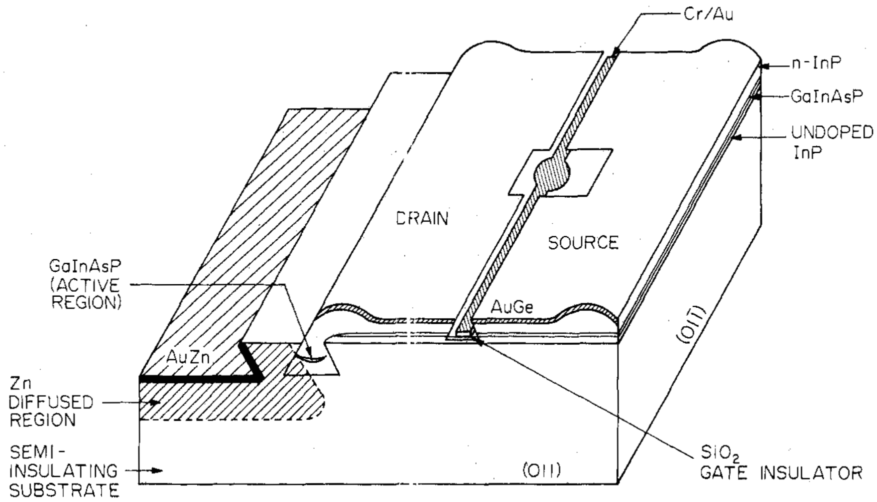

Fig. 11. An integrated buried laser metal insulator field effect transistor (MISFET) in the InP/GaInP crystal system (after [20]).

In examining the rationale for continued development of integrated optoelectronic circuits, we might mention the following reasons:

1) Independently of all other reasons, it should prove, eventually less expensive to combine electronic circuits with lasers and detectors monolithically rather than interconnect them by wiring in a hybrid fashion.
2) Monolithic integration should lead to smaller circuits and ones with greater ruggedness, hence, reliability.
3) The greatly reduced parasitic inductances and capacitances made possible by the shorter monolithic "wiring" should prove advantageous in high frequency applications, $f > 5$ GHz, which soon will be demanded of semiconductor based optoelectronic circuits and will be crucial for even higher frequencies.

I attempted in this paper to describe the beginning of integrated optoelectronic circuits. It seems to me that just like so many other technological developments–it is really a story of an idea whose time has come rather than of some brilliant sudden insight. I am grateful to have been at the right place and at the right time and to be able to work for fifteen years with the extremely talented graduate students and colleagues at Caltech.

I am also grateful for the foresightedness of the people of the

funding agencies who would allow us to go on working and "playing" for fifteen years on our dream of an "Integrated Optoelectronics" before it became fashionable and, thus more easily justifed. I could not finish this paper without thanking M. Stickley (formerly with the Advanced Research Projects Agency); R. Reynolds, S. Roosild (Advanced Research Projects Agency), A. Schutzman (National Science Foundation), and A. Shostak, L. Cooper at the Office of Naval Research, and H. Schlossberg at the Air Force Office of Scientific Research for continued support and personal involvement in the work described.

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