OPTICAL ELECTRONICS

A. Javan

Physics Department, Massachusetts Institute of Technology

N76-21511

In the radio and microwave frequency region, the science of electronic devices operating on the principles of alternating currents flowing through the device elements, is broadly known as radio and microwave-electronics. Its vast discipline encompasses the whole technology of classical electronic devices made up of vacuum tubes and solid state elements along with lumped circuits or distributed components; oscillators, amplifiers, converters, counters, etc., are just a few examples.

Quantum electronics, on the other hand, is based on entirely different principles. In this case, instead of electric current flow through individual device elements, electrons resonating in atoms or molecules determine the device properties. These devices are, accordingly, based on quantum mechanical concepts rather than classical; maser oscillators and amplifiers, quantum counters, etc., are examples of these in the radio and microwave frequency regions.

In order for an element to allow an alternating current at a high frequency to flow through it, its time constant, τ, must be less than or comparable to the period, T, of the alternating frequency current. An element's time constant is determined by its own inherent speed and the RC time constant of the lumped circuit to which it is coupled. In addition to this time domain requirement, a vast majority of radio or microwave electronic applications demand that the overall size of an element and its associated lumped circuit components be less than the wavelength corresponding to the alternating current frequency. This latter condition obviates problems due to phase shifts which can occur over distances larger than one wavelength and results in cancellation whenever the current through an element runs out of phase with respect to the voltage wave.

In the low radio frequency region, the dimensions of the component elements (that is, the vacuum tubes, transistors, tank-circuits, etc.) are generally considerably less than a wavelength. At higher frequencies, however, it is possible to distribute these components over distances exceeding several wavelengths; in these, the phases of currents in the various elements are kept in step with the voltage wave to prevent the cancellation.

In quantum electronics, one usually does not think in these terms; however, analogies exist – for one, an atom or a molecule's time constant is sufficiently short, allowing it to respond to frequencies where its resonances lie. And as for the phase consideration, we note that here inherently we deal with a distributed system with atoms or molecules filling volumes of dimensions exceeding a wavelength. The atoms' keeping up with the spatial phase of the electromagnetic wave follows from the laws of stimulated emission of radiation or the phase-matching criterion of the parametric processes. As a result, neither the time constant nor the phase requirements were at any time in the past a problem in our efforts to extend quantum-electronic devices into the optical regions; this became a reality with the advent of lasers early in the 1960s.

Extensions of radio and microwave electronics into optics, however, have required devising a high-speed element of microscopic size with a time constant less than an optical period and dimension less than one light wavelength. Starting in the mid-1960s, in a continuing series of research efforts (refs. 1 and 2), we succeeded in making a two-terminal high-speed junction element capable of responding at very high frequencies. And with it we have shown that it should be possible to extend the whole science of radio and microwave electronics into the far-infrared, infrared, and eventually the visible regions. While this is still in its infancy, these experiments, (which include some recent and as yet unpublished MIT works), show the future possibilities in this whole new set of technology, which we now identify as Optical Electronics.

Naturally, as in quantum electronics, optical electronic devices will be expected to fulfill substantially different types of need, compared to their counterpart devices in the radio or microwave regions. Similarly, optical electronic applications will lie in enormously different areas than existing laser applications. And the two fields in combination promise to play major parts in such diverse uses as advanced computer memory and holographic imaging schemes in real-time. Much further work, however, is needed to reduce these far-reaching possibilities (which are in large part as yet theoretical) to practice.

In these, the research workhorse will have to be highly-specialized microelectronic methods; examples include photolithography, electron-lithography, X-ray lithography, etc. Inspection shows that, with thin-film microelectronics, it should be possible to form on a substrate, for instance, an L-C tank-circuit of micro-size dimensions with a resonance frequency in the far-infrared or infrared. Such a tank-circuit can be integrated to a microscopic two-terminal high-speed deposited junction with nonlinear I–V characteristics. Such a unit can be used, e.g., as a phase bi-stable subharmonic parametric oscillator, driven with an external laser beam. Or, for a similar junction with a negative differential conductivity, the unit can be made to self-oscillate.

A useful tank-circuit will not necessarily be required to have a high-Q. For this, we need to be reminded that a radio-frequency oscillator can be made with an L-C circuit consisting of a coil and a capacitance with a Q of five or ten (occupying volumes with dimensions much less than a wavelength). An analogous situation can be envisaged for a deposited circuit forming the L-C tank of an oscillator, designed to oscillate, e.g., at a submillimeter frequency (see figure 1). Such an oscillator would not be a power oscillator, and, in fact, it might be used as an active unit internal to a device, (say in the form of a local oscillator), and with little or no energy coupled out of it.

Other embodiments can be envisaged in which a high-speed junction with negative differential conductivity is used as a bi-stable element, forming a high-speed flip-flop. This, along with a host of other possibilities, has far-reaching high-speed computer memory applications. For instance, an integrated system consisting of a large number of unit-cells can be envisaged in which all signal leads to the individual unit-cells are eliminated and, instead, each cell is communicated by light pulses (or with electron beams). (In the existing computer memory systems, the stray lead-capacitance limits the speed.)

One can also envisage a system in which the necessary bias-field for an active element is provided by integrating it to a deposited power supply consisting, e.g., of small rectifiers powered by an external radiation field. All these can, in principle, be done by focused laser beams or via integrated optics.

A summary of some early experiments and their immediate implications is as follows. The various developments followed the advent of a high-speed two-terminal junction element of microscopic dimension with a nonlinear I-V characteristic, and capable of supporting alternating currents at infrared frequencies (refs. 3 through 5). The element is used at these high frequencies as a diode, in much the same way as an ordinary rectifier frequency-mixer diode is used at radio frequencies. The optical diode consists of a metal-dielectric-metal junction in which the high-speed electric conduction process occurs due to quantum mechanical electron tunneling across the dielectric barrier. In a series of experiments, we have shown that, when subjected to an infrared radiation, alternating frequency current at the frequency of the applied radiation can flow through the junction. This takes place following the nonlinear I-V characteristics, which results in a sizable distortion of the infrared frequency current waveform. In fact, it is possible to clip the waveform and produce a square-wave at the corresponding frequency. Further, the current rectification results in conversion of the applied sine-wave to a dc voltage appearing across the diode. Two different frequencies can be mixed in the diode, with the result that detectable infrared radiation is emitted from the diode at new synthesized frequencies (ref. 6). In addition, it has been possible to mix in the diode two infrared frequencies differing by more than several octaves, and thus compare the two precisely (ref. 7). This has enabled constructing a frequency multiplier chain to compare a laser frequency with a microwave clock. By now, the method has been used at MIT and a number of centers internationally, to determine precisely the frequency of laser radiation in highly accurate spectroscopic observation, and in precise measurements of the speed of light; major contributions have been made to this field by K. Evenson (ref. 8), J. Hall (ref. 9), and their colleagues at NBS. The MIT activities have now shifted to the exploitation of the high-speed junction elements in optical electronic devices outlined in this report.

The early models of the diode consisted of a mechanically-contacted unit. In a recent major advance, a new version of the diode element is developed in which the element is printed on a substrate (ref. 10). This is done by thin-film vacuum deposition and the application of photolithography and micro-electronics. The junction is integrated to a small infrared-frequency antenna for coupling to the radiation field. With this method, instead of one diode element, it is now possible to deposit simultaneously a large number of them and, when desired, distribute them in the form of a phased-array configuration at infrared wavelengths. Among several new applications, a two-dimensional array of these high-speed diodes can make possible superheterodyne imaging in infrared; the holographic application mentioned above is based on this principle.

In a series of as yet unpublished MIT works, we are able to show that, in our high-speed metal-dielectric-metal junction, it should be possible to control the growth of the dielectric layer (which is required to have a thickness under 10 Å) and, in fact, reproduce tunneling barriers whose properties are known from previous experiments on large-area tunneling junctions. (The latter junctions are low-speed, with cutoffs in the MHz region.) The large body of the existing theoretical and experimental information in quantum mechanical electron tunneling in large area metal-dielectric-metal junctions (refs. 11 and 12) can now be extended to our case. We now know that it should be possible to construct high-speed junctions with I-V characteristic curves resembling the previously known low-speed junctions. For instance, it is known that, in a multi-barrier tunneling junction, or in a Josephon tunneling junction between two dissimilar superconductors, I-V characteristics with negative differential conductivity can be obtained; we can now expect to manufacture high-speed versions of these same junctions for use as bi-stable elements and other computer application. Furthermore, there are cases in which the nonlinearities of the I-V curves are known to be very large (ref. 13). Estimates show that if these are reproduced in the form of high-speed junctions, conversion of an applied radiation to dc voltages by rectification in such junctions can be obtained with nearly unity efficiency. Beyond these, it is to be noted, multi-terminal high-speed elements of microscopic dimensions can also be envisaged. A high-speed triode, for instance, would make possible new classes of high-frequency amplifiers with dimensions of tens of micron or less.

Far from implying that the above are all within an immediate reach, it is to be emphasized that a great deal of high technology research is required to establish all these various possibilities.

REFERENCES

1. For a review, see: Javan, A.: Modern methods in precision spectroscopy; a decade of development. Fundamental and Applied Laser Physics, Proceedings of the Esfahan Symposium, edited by Feld, Javan and Kurnit, John Wiley Interscience, 1973, p. 295. This article gives references to early works in frequency mixing including the works of K. Evenson and colleagues at NBS.

2. For a review discussion of physical processes and some future applications, see: Javan, A.; and Sanchez, A.: Extension of Microwave Detection and Frequency Measuring Technologies into the Optical Region. Laser Spectroscopy, edited by Brewer and Mooradian, Plenum Press, 1975, p. 11. For other works, see: Twu, Bor-Long; Schwarz, S. E.: Mechanism and Properties of Point-Contact Metal-Insulator-Metal Diode Detectors at 10.6μ. Appl. Phys. Letters Vol. 25, 1974. p. 595. Schwarz, S. E.: Triode Amplifiers for the Infrared. IEEE J. of Quantum Electronics, Vol. Q. E. 10, 62, 1974. Wang, S. Y.: Favis, S. M.; Siu, D. P.; Jain, R. K.; and Gustafson, T. K.: Enhanced Optical Frequency Detection with Negative Differential Resistance in Metal-Barrier-Metal Point-Contact Diodes, Appl. Phys. Letters Vol. 25, 1974, p. 493.

3. Hocker, L. O. et al: Frequency Mixing in the Infrared and Far-Infrared Using a Metal-to-Metal Point Contact Diode. Appl. Phys. Letters Vol. 12, 1968, p. 401.

4. Daneu, V.; Sokoloff, D. R.; Sanchez, A.; and Javan, A.: Extension of Laser Harmonic-Frequency Mixing Techniques into the 9μ Region with an Infrared Metal-Metal Point-Contact Diode; Appl. Phys. Letters Vol. 15, 1969, p. 398.

5. Sokoloff, D. R.; Sanchez, A.; Osgood, R. M.; and Javan, A.: Extension of Laser Harmonic-Frequency Mixing into the 5μ Regions, Appl. Phys. Letters Vol. 17, 1970, p. 257.

6. Sanchez, A.; Singh, S. K.; and Javan, A.: Generation of Infrared Radiation in a Metal-to-Metal Point-Contact Diode at Synthesized Frequencies of Incident Fields: A High-Speed Broad-Band Light Modulator. Appl. Phys. Letters Vol. 21, 1972, p. 240.

7. Javan, A.; and Sanchez, A.: loc cit, ref. 2.

8. Evenson, K. M.; Wells, J. S.; and Matarrese, L. M.: Absolute Frequency Measurements of the CO_2 CW laser at 28 THz (10.6μ). Appl. Phys. Letters Vol. 16, 1970, p. 251. See also: Evenson, K. M. et al.: Speed of Light from Direct Laser Frequency and Wavelength: Emergency of a Laser Standard of Length. Laser Spectroscopy, edited by R. G. Brewer and A. Mooradian, Plenum Press, 1975.

9. Hall, J.: Saturated Absorption Lineshape. Fundamental and Applied Laser Physics, Proceedings of the Esfahan Symposium, edited by Kurnit, Javan, and Feld, John Wiley Interscience, 1973, p. 463.

10. Small, J. G. et al.: A. C. Electron Tunneling at Infrared Frequencies. Appl. Phys. Letters Vol. 24, 1974, p. 275.

11. Giaver, Ivan: Electron Tunneling and Superconductivity. Science, Vol. 183, 1974, p. 1253.

12. Tsu, R.; and Esaki, L.: Tunneling in a Finite Superlattice. Appl. Phys. Letters Vol. 22, 1973, p. 562.

13. Shen, L. Y. L.; and Rowell, J. U.: Zero-bias Anomalies-Temperature, Voltage and Magnetic Field Dependence. Phys. Rev. Vol. 165, 1968, p. 566.

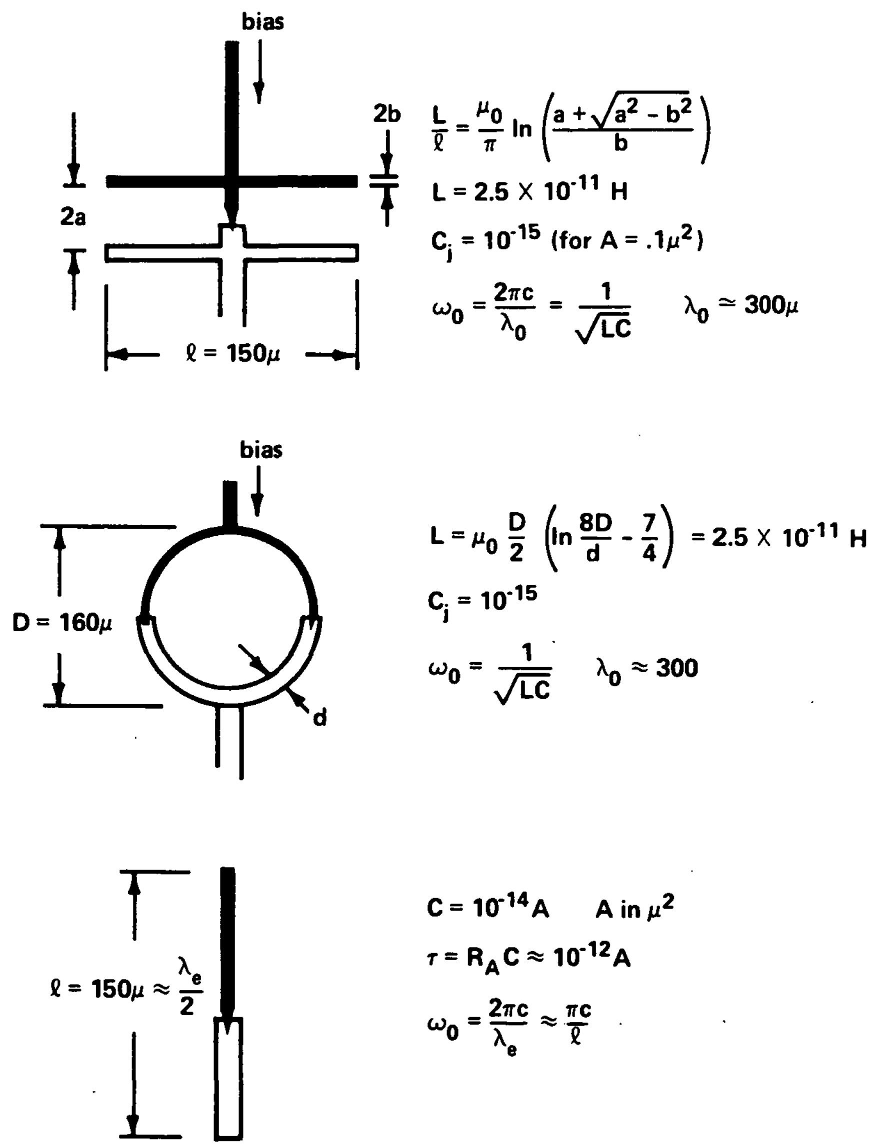

Figure 1.– Tank circuits resonating in the far infrared. Capacitance in the lumped circuits are dominated by the junction capacitance.

DISCUSSION

Ernest Brock, Los Alamos Scientific Laboratory – Professor Javan, I believe all of us, in the spirit of your talk, are feeling stimulated response! I wanted to raise the issue of fabrication. The materials you are working with, for example, nickel and chromium, are evaporated and come down as polycrystalline materials, do they not?

Ali Javan: Yes, although we haven't studied the epitaxy, they probably do. I must mention that a major problem we have with the evaporated junctions, although we can print one or one hundred of them, the yield is very poor. Sometimes the yield is only 1 or 2 percent, at other times we can get to 40 to 50 percent. But there are holes and we have reason to believe they are polycrystalline.

Ernest Brock, LASL – With regard to polycrystalline aspects, we all know that in tunneling phenomena, not only the Fermi level but also the work function are important in establishing the contact potential difference. With a polycrystalline material you have some sort of average work function. If you could work with single crystal surfaces in contact with one another, then one would not have a spectrum, even with nickel and chromium, of the order of a volt of contact potential difference.

Ali Javan: Yes. Could I say that we have seen effects with a few junctions which we could explain as two junctions, one about 6 Å thick, the other about 7 Å thick, but in parallel. Sometimes the average is not random. By all means we have to go into the epitaxy.

Ernest Brock, LASL – One other aspect – with nickel you're working with a face-centered cubic material. Cadmium, perhaps, comes down hexagonal close packed, perhaps in a cubic modification. So far as going to cool temperatures, the detailed lattice structure would be quite important, you know the k vector, and so I'm wondering if you should be considering the phonon bath in which you are doing this, especially as your techniques become more sophisticated.

Ali Javan: Absolutely. Frankly, there is a whole field ahead and we are just beginning. So much will depend upon what we can do in the areas of microelectronics and thin films. There are only a few sophisticated microelectronics laboratories – we are attempting to duplicate a poor man's version of one, but much remains to be done. For example, we are looking forward to the possible use of electron microscope techniques for laying down 1000 Å x 1000 Å junctions. Also we wish to control oxide thickness carefully – quite possibly interesting photo emission effects can be seen. I am looking forward to hearing Dr. Gustafson's talk since he has been working in the interesting visible range of wavelengths which is a marvelous area to study barrier heights i.e. where the wavelength exceeds the barrier height.

Ned Rasor, Rasor Associates – Just a comment relative to the previous question. That is, you do not have to have single crystals to have single work function surfaces. You have a polycrystalline surface and then etch it just to expose a single crystal plane.

Ali Javan: May I also say that another thing enters here and that is that for cross sections like 1000 Å, the current densities in these junctions are extremely high. Thus we shouldn't think of a one-electron picture where the tunneling electron sees its image charge. We have to consider cooperative phenomena here.