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Authors

A.J
Hebert

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A. J. Hebert

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PHOTOVOLTAIC EFFECTS IN LASER DIODES*

A. J. Hebert
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The photovoltaic effects observed in gallium arsenide and gallium arsenide phosphide laser diodes indicate that they may be used as broad band photodetectors, as temperature sensing devices, or as solar cells. Similarities between the photovoltaic properties of semiconductor pn junctions and superconducting Josephson junctions suggest the possibility of an e/h experiment and voltage standardization with near infrared or visible radiation.

Studies have been made previously on the photoelectric effects of n-type gallium arsenide (GaAs) high resistivity crystals,[1,2] and on GaAs thin film solar cells.[3] Platinum GaAs barrier cells yielded solar energy conversion efficiencies of approximately 5% with an input area of 0.2 cm^2. Larger-than-band gap photovoltages have been observed in GaAs and several other semiconductor films.[4,5]

This letter reports on the observation of photovoltaic effects which result when GaAs or gallium arsenide phosphide (GaAsP) laser diodes[6] are irradiated along their lasing axis or parallel to the pn junction plane with photons having an energy greater than the GaAs or GaAsP band gap.

The maximum photovoltage, E_{max}, generated by the laser diodes across 10^7 to 10^9 ohm loads was found to be linear with respect to temperature. E_{max} is defined here as the voltage at which an increase in incident light intensity produces no increase in photovoltage. The observed values of E_{max} ranged from 0.61 eV at 295°K to 1.23 eV at 4.2°K (liquid He boiling point) and can be expressed by the following equation:

$$E_{max} = E_0 - mT \qquad (1)$$

where $E_0 = 1.24\ (2)$ eV, and $m = 2.135\ (20)$ mV/°K.

The observed voltage output polarity is the same as that applied when operating the diodes as lasers, i.e., p positive. E_{max} did not vary when the polarization of the exciting light was changed relative to the junction plane. A power input of approximately 20 mW/cm^2 was found to be adequate for the observation of E_{max} across 10^7 to 10^9 ohms for the GaAs and GaAsP laser diodes investigated. E_{max} was the same for these devices when irradiated with 6328 Å light from a He-Ne continuous laser or with light from a tungsten lamp.

With care, it should be possible to calibrate a laser diode for temperature measurements to better than 0.1%. Input photon power need only be approximately 2 μW for 10 msec to obtain a reading of the above accuracy. The photon source could either be located at a distance from the laser diode temperature sensing chip or could be an equally small laser or light emitting diode mounted very close to the sensing chip. Tests have not yet been made to determine the feasibility of using a smaller input power and calibrating at voltages less than E_{max}.

The photovoltaic effect and the photocurrents observed are very sensitive to alignment. It has not yet been determined whether this is due mainly to reflection effects, passage of the voltage generating photons along a narrow junction plane, or a combination of these effects. In any case, the observed directionality indicates that laser diodes may be useful as broad band radiation direction sensors.

The photovoltaic effect is equally strong when photons are incident perpendicular to the lasing axis and parallel to the junction plane. The laser diodes used in these studies did not seem to have opaqued or roughened sides.

Photocurrents were readily observed at room temperature with an electrometer and power inputs of 10^{-10} watts/cm^2 from a monochromator set at 9000 Å. This would indicate an ability to readily detect 10^{-14} watts if the entire exposed polished face of the diode is assumed to contribute to the effect, and 10^{-15} to 10^{-16} watts if only the laser output area of 10^{-5} to 10^{-6} cm^2 is the active photon input site. The detection efficiency falls off sharply above 9000 Å for GaAs and above 7800 Å for GaAsP.

Such sensitivities suggest the possible use of single laser diodes with appropriate optics as solid state photodetectors. The small sizes also point up their possible usefulness in arrays as solid state kinescopes and image intensifiers.

Studies with a series array indicated that all diodes must be uniformly irradiated or the efficiency drops drastically. This effect is not so pronounced in a parallel arrangement but there is a slight drop in efficiency, (approximately 10%), if one of two diodes in parallel is not irradiated.

With a 24 diode series array[6] and approximately 200 mW/cm^2 of incident tungsten lamp energy at room temperature, E_{max} amounted to 4 eV. One would expect roughly 14 eV if each diode were well aligned and properly irradiated. An E_{max} of 1.2 eV at room temperature was readily obtained for a series of two laser diodes when properly aligned. In a parallel arrangement of two diodes, E_{max} is 0.6 eV and the power output is doubled, as one would expect.

The laser diodes studied may be used directly as input to phase sensitive lock in detectors when the incident photons are modulated at the reference rate. There is no need for a biasing voltage. The observed rise and fall times for the devices are 0.5 msec.

Power conversion efficiencies for the single diodes were measured at room and liquid nitrogen temperatures. At liquid nitrogen temperature the power conversion efficiency for 20 mW/cm^2 6328 Å light is 50% if one assumes the active input area to be 10^{-5} cm^2 and 5% if it is assumed to be the entire polished end area of roughly 10^{-4} cm^2. The efficiencies for a 20 mW/cm^2 tungsten lamp or 6328 Å laser input at room temperature were roughly a factor of three lower.

An obvious extension of these results would be to study other semiconducting pn junctions and laser diodes in hope of finding similar sensitivities at longer wavelengths. Photovoltaic effects and high quantum efficiencies, (25%), have been reported for indium antimonide-metal oxide semiconductor structures[7] but the detectivity is said to fall short of conventional InSb diode detectors.

A Raytheon InAs laser diode (band gap approximately 0.41 eV) gave no observable photovoltaic effect at room temperature and yielded only 1 mV at 77°K for an input of 20 mW/cm^2. The photocurrent was also several orders of magnitude lower than that observed for comparable light inputs to GaAs. This may be related to the low resistance or poor lasing efficiency of the device.

The observed photovoltaic outputs of the GaAs and GaAsP laser diodes were found to drop sharply if the diodes had been damaged or showed a reduced lasing efficiency. This would suggest that a simple photovoltaic test of laser diodes might be a rapid and economical means of quality control. Such testing might also turn up more efficient detectors.

These studies were begun with the hope of observing laser emission with an input square wave pulse or constant voltage (CW laser operation) corresponding to the band gap. Laser diodes have been pulsed and operated CW at both liquid helium and nitrogen temperatures. Thus far only spontaneous emission has been observed, but the applied pulse voltage or constant voltage matches the peak of the several hundred angstrom wide output radiation to an accuracy of 1% using the Einstein relationship:

$$eV = h\nu - \phi \tag{2}$$

and assuming ϕ is negligible. The applied pulse voltage at which output radiation is first detected is approximately 100 mV below the detected photon energy. This may be due to excitation of lower levels accompanied by mixing effects.

One might compare these experiments to the AC Josephson effects observed in superconducting junctions.[8,9] The Josephson relationship,

$$2\ eV = nh\nu \quad , \tag{3}$$

has been used at microwave frequencies to determine e/h.[10] This also brings to mind the work of Bube[1] on GaAs crystals. Bube observed several energy levels below the conduction band, and one at 1/2 the band gap energy. Sturge[2] has also observed absorption structure with thresholds at roughly 1/2, 1/3, and 1/6 of the energy gap.

Equation (1) is similar in form to the dark conductivity expression given by Bube[1]:

$$E_f = E + kT\ \ell n \left[\frac{N_A}{N_D - N_A}\right] \quad , \tag{4}$$

where E_f is the distance between the bottom of the conduction band and the Fermi level, and E is the activation energy of the uncompensated donor centers in partially compensated n-type crystals with N_D donors partially compensated by N_A acceptors in the range where $n << N_A$.

The observed E_{max} at 77°K in the present experiments is in fair agreement with the low energy quenching cutoff observed at 1.15 eV by Bube[1] at 90°K for partially compensated n-type crystals. He attributes this to a sensitizing level lying about 0.3 eV below the conduction band.

Perhaps laser diodes with lower thresholds will allow a more accurate appraisal of their possible use as voltage standards or for a determination of e/h. The use of smaller laser diodes and lasing excitation at the band gap energy may allow the observation of photon stimulated population inversion and a photovoltaic output which might correspond more closely to the incident photon energy.

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FOOTNOTES AND REFERENCES

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