OPTICAL RECTIFICATION AND PHOTON DRAG IN P-TYPE GaAs AT 10.6μm AND 1.06μm

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Photoelectric effects occurring in p-type GaAs under illumination by laser radiation are discussed. These effects fall into two distinct types, optical rectification and photon drag, which can be distinguished by detailed examination of their tensor properties.

1. INTRODUCTION

Neglecting terms linear in electric field, higher order photoelectric effects can be written as a series of terms which are combinations of powers of the light electric field, $\vec{E}$, and the unit propagation vector, $\hat{q}$. Taking this expansion to first order in $\hat{q}$ and second order in $\vec{E}$, we can write the non-linear part of the photoelectric fields as:

$$E_i^{NL} = I\, R_{ijk}\, p_j\, p_k + I\, T_{ijkl}\, q_j\, p_k\, p_l \qquad (1)$$

where p_j is the component of the unit polarisation vector in the j direction and I the light intensity. The first term on the right hand side of the expression is optical rectification; the second term, linear in photon momentum, is the photon-drag effect.

Optical rectification has been reported in Te [1] and KDP and K*DP [2]. It arises when electronic high frequency nonlinearities result in a net d.c. shift. Photon drag, which appears in Ge [3,4], is the result of the momentum of the photon being distributed unequally in k-space amongst the excited carriers, with a collective shift in the equilibrium distribution function leading to the appearance of a net current. Since the classification of this effect, detectors have appeared for use with high power CO_2 lasers.

An extention of the photon-drag effect to the visible region of the spectrum should be possible; however, Ge would not be very suitable because interband transitions lead to a very high absorption coefficient. For this reason, GaAs has been investigated, with particular attention paid to the region around 1μm. In this paper we report the observation of optical rectification and photon-drag at 10.6μm and 1.06μm.

2. BACKGROUND

2.1. OPTICAL RECTIFICATION

The electric field generated by optical rectification is given by the first term in Eq.1. GaAs is a III-V semiconductor possessing $\bar{4}3m$ symmetry;

this symmetry reduces the number of independent terms in the tensor R_{ijk} to one, the only non-zero terms being $R_{123} = R_{132} = R_{231} = R_{213} = R_{321} = R_{312}$. Carrying out the implied summation in Eq.1. and setting $D = R_{123}$, the following expression for the photoelectric field is obtained.

$$E_i = 2\ I\ D\ p_{i+1}\ p_{i+2}$$

Representing by $E(\hat{r},\hat{q})$ the field measured in the $\hat{r}$ direction when the light propagates in the $\hat{q}$ direction, we can summarise the electric field polarisation direction dependence for a number of orientations. In Fig.1. is shown the convention used; $\hat{q}$, $\hat{a}$, and $\hat{b}$ form an orthogonal set of unit vectors with the light polarisation lying in the $\hat{a}\hat{b}$ plane.

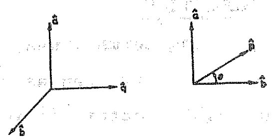

Fig. 1. Convention used to describe polarisation unit vector $\hat{p}$ in terms of crystal axes a and b; the propagation direction unit vector, $\hat{q}$, completes the orthogonal set.

$E(100,100) = I\ D \sin 2\theta$	$E(001,100) = 0$	$a = [010]$	$b = [001]$
$E(110,110) = 0$	$E(1\bar{1}0,110) = -I\ D \sin 2\theta$	$a = [001]$	$b = [1\bar{1}0]$
$E(111,111) = -\frac{ID}{\sqrt{3}}$	$E(11\bar{2},111) = -\frac{2ID}{\sqrt{6}} \cos 2\theta$	$a = [1\bar{1}0]$	$b = [11\bar{2}]$

The optical rectification tensor R_{ijk} can be transformed into a non-linear susceptibility tensor d_{ijk}; using the frequency and subscript permutation rules in [5], this d_{ijk} is directly related to the linear electro-optic tensor r_{jki}. Combining these results gives;

$$R_{ijk} = \frac{2n^4 \varepsilon_o}{(\varepsilon-\varepsilon_o)} \frac{(\mu_o)^{\frac{1}{2}}}{(\varepsilon)^{\frac{1}{2}}} r_{jki} \qquad (2)$$

We will use this relationship later in comparing the value of R_{ijk} measured with that obtained using Eq.2. and the accepted value for r_{jki}.

2.2. PHOTON DRAG

In [6] is set out the tensor nature of photon drag in a discussion of the results for Ge. The tensor for $\bar{4}3m$ materials will differ from that for Ge because of the lack of inversion symmetry. This fact leads to the appearance of a single new term Q associated with the anti-symmetric part of T_{ijkl}. With the definitions of S and P the same as given in [6], the electric field arising from the photon-drag effect can be written as:

$$E_i = I(Sq_i + (P-S)\ q_i p_i^2 + 2Qp_i\ (p_{i+1}q_{i+1} - p_{i+2}q_{i+2}))$$

Using the same convention given in Fig.1., we can summarise a few photon-drag fields.

$$E(100,100) = IS \qquad E(001,100) = 0$$

$$E(110,110) = I\{S + \frac{(P-S)}{2}\cos^2\theta\} \qquad E(1\bar{1}0,110) = -I\,Q\cos^2\theta$$

$$E(111,111) = I\,\frac{P+2S}{3} \qquad E(11\bar{2},111) = I\{\frac{S-P}{3\sqrt{2}}\cos 2\theta + \frac{2Q}{\sqrt{6}}\sin 2\theta\}$$

Notice the effect of the Q term is to add a term in quadrature with the normal photon drag as can be evidenced in $E(11\bar{2},111)$. In general this will result in a field of the form $A\cos(2\theta+\phi)$ where ϕ is a measure of the strength of Q.

3. EXPERIMENT

The 10.6μ, measurements were done with a q-switched CO_2 laser, operating at 200 pulses per second and capable of giving 100kW peak power in 150nsec half width pulses. The output power of the laser was continuously monitored using a Ge photon-drag monitor. Signals from the GaAs were amplified with a Hewlett Packard pulse amplifier type HP 462A and displayed on an oscilloscope. For the 1.06μm measurements, a q-switched Nd^{+3}:YAG laser was used giving 3kW peak power in 150nsec pulses at a 1 kHz repetition rate.

The GaAs material was Cd doped with carrier concentration $p=3\times10^{16}/cm^3$ and a mobility of 225 cm^2/V-sec. Electrodes were alloyed onto polished samples by heat treatment of In:3% Zn contacts. If the electrodes did not alloy correctly, then large photoelectric effects would appear if the light were directed onto the contact region. These voltages were always more evident at 1.06μm than at 10.6μm.

In Fig.2. shown combined are results for measurements at 10.6μm and 1.06μm on a sample whose axes are $\hat{q} = [110]$, $\hat{a} = [001]$, $\hat{b} = [1\bar{1}0]$. Combining the results of section 2.1 and 2.2 we see that the form of the field should be:

$$E^{NL}(1\bar{1}0,110) = -I(D\sin 2\theta + Q\cos^2\theta)$$

Clearly, the result show no $\cos^2\theta$ dependence, and the term Q for GaAs is much smaller than D. In a similar way, other orientations give relationships between the various terms. The results of the measurements at 10.6μm and 1.06μm are included in the table below, with corrections for reflection and absorption included.

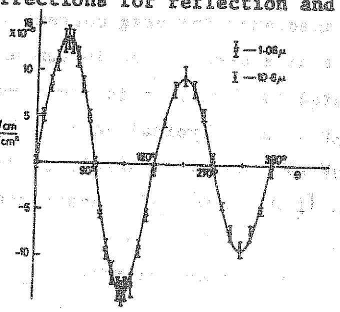

Fig.2. Plot of experimental optical rectification versus angle. $0\leq\theta\leq\pi$: 1.06μm; $\pi\leq\theta\leq 2\pi$: 10.6μm. The curve is a plot of $A\sin 2\theta$ where : A = 13.6 for 1.06μm points; A = 9.4 for 10.6μm points. Units are $10^{-8}\ \frac{V/cm}{W/cm^2}$.

Table 1. Value of the tensor coefficients at $300^{\circ}K$ for GaAs at 1.06μm and 10.6μm (units are 10^{-10}m/A)

	|D|	S	P	|P-S|	|Q|
1.06 μm	14	-1.4	-2.2	0.8	<0.6
10.6 μm	15	-	-	8.8	<0.6

4. DISCUSSION

From the table above, it will be noticed that S and P could not be determined at 10.6μm. An experimental difficulty was encountered in obtaining uniform electric field orientation in longitudinal samples. Coupled together with high absorption due to intervalence band transitions, this inevitably led to mixtures of transverse plus longitudinal field being measured.

The results of the measurements were all consistent with the photoelectric effect being described by a tensor of third rank plus a tensor of fourth rank. In section 2.1 it was pointed out that the optical rectification coefficient, D, is proportional to the linear electro-optic coefficient $r_{jki} = R$. The value of R is 1.6×10^{-12}m/V [7]. Using Eq.2. and the value for |D| at 1.06μm given in the above table, R is computed to be 0.5×10^{-12}m/V, which is in good agreement with the directly measured value.

In [3] an expression for the photon-drag field using a classical treatment is given. Writing $E^{NL}=TI$, this expression reduces to $T=\alpha\rho\mu/c$ where α, ρ and μ are the absorption coefficient, resistivity and mobility respectively. Using the parameters for the GaAs under investigation, $T=13\times10^{-10}$m/A. If we compare this value with any of the values for S,P or P-S above, we see that the results at 10.6μm are in better agreement than those at 1.06μm. This difference in the photon drag results might best be explained by reference to the valence band structure of GaAs. The 1μm transition will proceed from the split off to the heavy hole band and will occur at larger values of k than the light to heavy hole transition at 10μm. The photon drag current is dependent not only on the scattering times of the excited carriers, but also on the derivative of the distribution function $\frac{\partial f(k)}{\partial k}$. The distribution function will be tailing off for the 1μm transition and as a consequence the drag current will be suppressed.

Ge as a detector at 10.6μm has been used extensively and has been fabricated as a monitor in the form of an optical bridge for determining pulse lengths [8]. Typical sensitivity for a $1cm^2$ cross-section, 1cm long bar is 100μV/kW. Using a sample of P-type GaAs with ρ= 1Ω-cm, 90μ thick oriented in a [110],[1$\bar{1}$0],[001] configuration, the peak sensitivity would similarly be 100μV/kW. Used in the form of an optical bridge, the sample resolving time would be approximately 1psec. Coupled together with some thin film non-linear absorber, very high resolution should be attainable at low cost, resulting in a useful tool for use with high power mode-locked Nd^{+3} lasers.

5. CONCLUSION

It has been shown that in a III-V semiconductor possessing $\bar{4}3m$ symmetry, a photoelectric effect possessing third and fourth rank characters is expected. The terms in this tensor have been measured for p-type GaAs. The optical rectification effect (3rd rank tensor) is of sufficient magnitude to serve as a fast detector at 1.06μm. Clearly it will never replace existing photodiodes in sensitivity, but properly fabricated, they can be used in an optical bridge for measuring pulse length.

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