Performance of photon drag and photon drag-optical rectification detectors in the 2 to 33 μm range

A.A. SERAFETINIDES, A.K. KAR, M.F. KIMMITT

Previous studies of the spectral response of p-Ge photon drag and n-GaP photon drag-optical rectification detectors have been extended. Measurements have also been made of the spectral response of p-Si photon drag, p-GaP photon drag-optical rectification and p-GaAs photon drag-optical rectification detectors. The wavelength range of main interest is between 2 and 11 μm, (HF, HCl, HBr, H_2O vapour and CO_2 lasers), but some measurements have also been made at 28 and 33 μm, (H_2O vapour laser).

P-type germanium is a well established material for the construction of fast room temperature photon drag detectors at 10.6 μm.[1] However, p-type germanium cannot be used in the 2 to 3 μm range (HF laser range), due to occurrence of two photon absorption, nor usefully in the 4 to 5 μm range (HBr laser range) due to the inversion of the sign of the photon drag signal at 4.25 μm. Between 25 and 35 μm (H_2O vapour laser range), the very high lattice absorption of germanium makes it an unsuitable detector material. Moreover, the response of detectors made out of p-type germanium is very sensitive to wavelength variation and the sign of the signal changes no less than five times between 2.5 and 11 μm.[2,3] Therefore, alternative materials were investigated. We have now extended previous work on p-Ge[2,3] and n-GaP[4] and we also report on photon drag in p-type Si and photon drag and optical rectifiction in p-GaAs and p-Gap.

Theory

GaP and GaAs lack inversion symmetry and therefore optical rectification occurs,[4] in addition to photon drag. Both effects were studied by Gibson et al[4] on n-type GaP and by Doviak and Kothari[5] on p-type GaAs.

Including only terms linear in intensity I, the generated electric field component E_i can be written as:

$$E_i = I[R_{ijk}p_jp_k + T_{ijkl}q_ip_kp_l] \quad (1)$$

where p_j, p_k, p_l are the unit polarization vector components of the radiation and q_j is a unit vector in the propagation direction. The tensor R_{ijk} describes the optical rectification and the tensor T_{ijkl} describes the photon drag effect.

The photon drag equation for m3m symmetry crystals can be written in terms of two coefficients S and P as:

$$E_i(\text{P.D.}) = I[sq_i + (P-S)q_ip_i^2] \quad (2)$$

and for $\bar{4}$3m symmetry in terms of three coefficients S, P and Q as:

$$E_i(\text{P.D.}) = I[Sq_i + (P-S)\,q_ip_i^2 + 2Qp_i\,(p_{j+1}q_{j+1} - p_{j+2}q_{j+2})] \quad (3)$$

The optical rectification contribution in $\bar{4}$3m crystals can be written as:

$$E_i(\text{O.R.}) = 2IDp_{i+1}p_{i+2} \quad (4)$$

where D is the only non-vanishing independent coefficient in R_{ijk}.

In practice we measure either the longitudinal voltage V_L given by:

$$V_L = \frac{(1-R)W\exp(-K1)[1-\exp(-KL)]}{AK} \left[\times \frac{[P,S]}{1+R\exp(-KL)} + \frac{[D]}{1-R\exp(-KL)}\right] \quad (5)$$

or the transverse voltage V_T given by:

$$V_T = \frac{(1-R)Wy}{A(1-R^2e^{-Kd}} \times \left[[P,S]\,(e^{-Kl} - Re^{-2Kd+Kl}) + [D]\,(e^{-Kl} + Re^{-2Kd+Kl})\right] \quad (6)$$

These voltages are generated between the contacts made near the end of the rod samples, as shown in Fig. 1. R is the reflection coefficient, K is the absorption coefficient, A is the area of the detector and W is the power of the beam falling on the detector. The factors $[P, S]$ and $[D]$ are the appropriate $E(\mathbf{q}, \mathbf{r})$ factors with $\mathbf{q}$ the direction of radiation propagation and $\mathbf{r}$ the direction along which voltage is measured. A number of these factors are tabulated in[5].

Experimental

The experimental results were obtained by using short high power laser pulses from line tunable HCl and HBr lasers described in,[3] the line tunable HF and CO_2 lasers described in [4] and an H_2O vapour laser. The H_2O vapour laser was a pulsed longitudinally excited laser. When a CaF_2 Brewster window terminated one end of the discharge tube the lasing wavelengths were limited to three lines around 7 μm. With a silicon window most of the laser energy was found to be in two strong lines at 28 and 33 μm.

All the experiments were undertaken on rod shaped samples; ⟨100⟩ and ⟨111⟩ orientated rods of p-Si and p-Ge, ⟨110⟩ and ⟨111⟩ orientated rods of p-GaP and ⟨100⟩, ⟨110⟩ and ⟨111⟩ orientated rods of p-GaAs and n-GaP. The main characteristics of specimen used in investigations are shown in Table 1.

The authors are with the Department of Physics, University of Essex, Colchester, UK. Received 4 April 1978.

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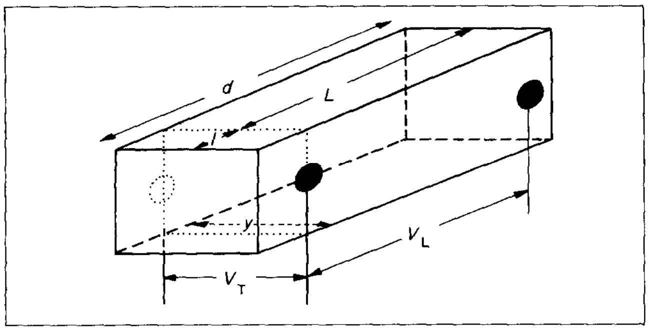

Fig. 1 Geometry of the samples used for transverse (V_T) and longitudinal (V_L) measurement

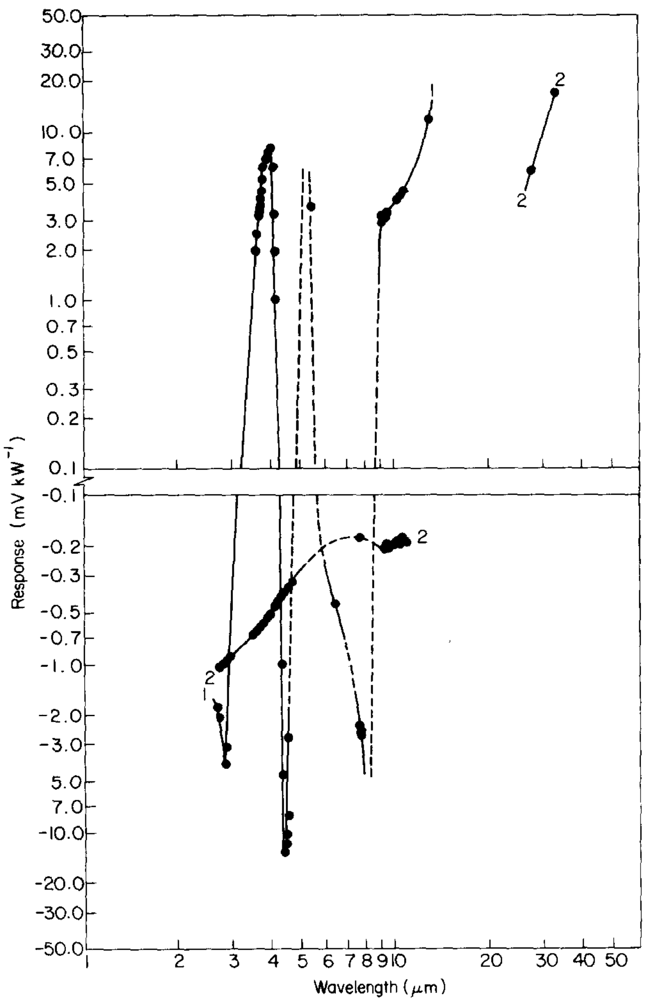

Fig. 2 The variation of the maximum response of the longitudinal photon drag detectors. (1)—p-type Ge, (2)—p-type Si

Table 1.

Specimen	Type of conductivity	Doping	Resistivity in ohm cm	Carrier concentration in cm^{-3}
Si	p	B	30.0	4.5×10^{14}
Ge	p	Ga	2.0	1.7×10^{15}
GaP	n	Te	2.2	2.4×10^{16}
GaP	p	Zn	3.5	1.6×10^{16}
GaAs	p	Cd	1.0	3.0×10^{16}

The measured quantity in each case was the voltage developed between the contacts. The power incident on the sample was deduced from measurements of the total energy in the laser pulse using a joulemeter. The pulse shape was obtained from photographs of photon drag or photon drag optical rectification signals. The response of the detector was then deduced for a given wavelength and using either equation (5) or (6) (as appropriate) *S, P* and *D* were calculated. It should be noted that the absolute sign of *S, P* and *D* at a given wavelength cannot be determined from responsivity measurements though once the sign of any one coefficient is chosen at any wavelength the sign of all coefficients are determined.

Figure 2 shows the variation in response of the ⟨100⟩ orientated p-Si and p-Ge samples. The response of n-GaP, p-GaP, p-GaAs is polarization dependent. Figure 3 shows the response of ⟨100⟩ orientated longitudinal detector of n-GaP and p-GaAs, ⟨111⟩ orientated transverse detector of p-GaP around 10.6 μm and ⟨110⟩ orientated longitudinal detector at 3 μm at an orientation with respect to the incident laser polarization, where maximum response is obtained. The ⟨110⟩ transverse signals were very small in the 3 μm range and ⟨100⟩ orientated detectors were not available. The relevant information on the p-Ge response variation has appeared earlier.[2,3,6]

The measured values of *S, P* and *D* coefficients at 300°K for p-Ge, p-Si, p-GaAs and n-GaP are given in Table 2. Table 2 also includes $|S|$, $|P|$, $|D|$, and $|P - S|$

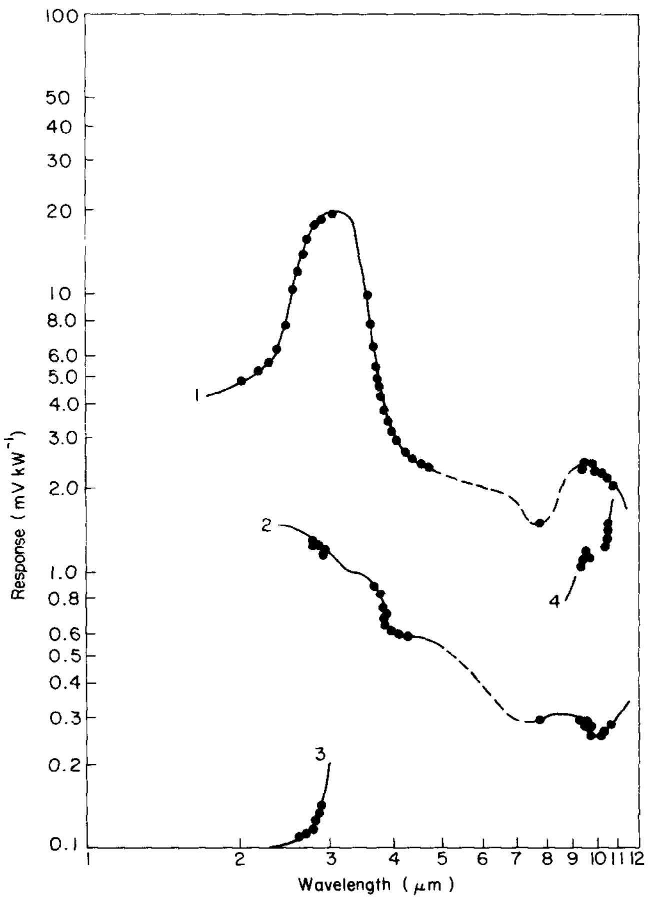

Fig. 3 The variation of the maximum response of the photon drag-optical rectification detectors. (1)—⟨100⟩ orientated longitudinal n-type GaP, (2)—⟨100⟩ orientated longitudinal p-type GaAs, (3)—⟨110⟩ orientated longitudinal p-type GaP, (4)—⟨111⟩ orientated transverse p-type GaP

Table 2.

	p – Ge		p – Si		n – GaP			p – GaAs			p – Gap			
λ (μm)	*S*	*P*	*S*	*P*	*S*	*P*	– *D*	*S*	*P*	*D*	|*D*|	|*P–S*|	|*S*|	|*P*|
2.73	–2.0	–2.0	–0.7	2.0	1.2	28.0	108.0	4.6	–	2.0	0.2	1.8	1.0	2.8
2.76	–2.8	–1.7	–	–	1.2	36.0	110.0	4.4	8.7	1.6	0.2	1.9	1.1	2.9
2.78	–3.7	–0.5	–	–	1.2	38.0	111.0	4.6	–	1.9	0.2	1.9	1.0	2.9
2.86	–3.5	–0.5	–	–	1.3	43.0	124.0	–	–	–	0.2	2.0	1.1	3.1
2.91	–3.6	–0.4	–0.7	2.0	1.4	45.0	137.0	4.5	8.6	1.8	0.2	2.2	1.1	3.3
3.00	0.0	–0.3	–	–	1.5	54.0	142.0	–	–	–	0.2	2.2	1.1	3.3
3.57	3.4	5.0	–	–	1.1	30.1	50.2	–	–	–	–	–	–	–
3.60	3.3	6.9	–0.6	1.5	1.0	24.9	41.0	2.0	5.2	0.8	–	–	–	–
3.64	3.0	6.7	–	–	0.9	15.0	35.0	–	–	–	–	–	–	–
3.67	3.8	5.1	–0.5	1.4	0.8	14.0	29.0	2.1	5.3	–0.8	–	–	–	–
3.70	3.8	4.8	–0.5	1.4	0.7	15.0	26.3	1.9	5.1	–0.7	–	–	–	–
3.71	3.7	4.7	–	–	0.6	12.8	23.5	–	–	–	–	–	–	–
3.74	3.6	4.6	–0.5	1.2	0.6	11.0	23.1	1.1	3.0	–0.5	–	–	–	–
3.77	4.7	5.2	–0.4	1.2	0.5	8.9	21.0	–	–	–	–	–	–	–
3.80	5.5	7.0	–	–	0.5	9.2	22.2	1.1	3.0	–0.5	–	–	–	–
3.84	6.7	6.8	–0.4	1.2	0.5	9.0	20.2	1.5	3.5	–0.5	–	–	–	–
3.88	6.2	6.4	–	–	0.5	8.9	20.0	1.7	–	–0.7	–	–	–	–
3.91	6.3	6.5	–	–	0.6	8.5	18.0	–	3.9	–	–	–	–	–
3.95	6.3	6.6	–	–	0.6	8.0	17.2	1.7	–	–0.3	–	–	–	–
4.10	1.8	2.7	–0.3	0.8	0.6	7.0	14.9	1.8	–	–0.3	–	–	–	–
4.26	–3.6	–4.2	–	–	0.6	6.8	14.4	2.0	3.2	–0.2	–	–	–	–
4.30	–11.5	–12.0	–0.3	0.8	0.6	6.6	14.2	2.0	–	–0.2	–	–	–	–
4.40	–9.4	–10.0	–	–	0.6	6.5	14.0	2.1	3.8	–0.1	–	–	–	–
7.71	–9.9	–10.2	–0.2	–	1.0	3.3	6.9	4.4	–	3.3	–	–	–	–
9.30	4.8	16.0	–0.3	0.7	1.2	10.0	11.6	4.3	17.3	7.2	35.0	65.0	–	–
9.57	9.2	20.6	–0.3	0.6	1.2	9.1	11.7	5.7	17.9	8.6	40.2	71.9	–	–
10.26	13.0	23.7	–0.2	0.7	1.4	9.5	11.1	7.0	16.8	8.9	59.2	82.0	–	–
10.59	13.7	24.5	–0.3	0.8	1.0	11.1	11.0	6.1	16.4	8.8	64.3	105.6	–	–
10.69	14.0	24.7	–0.3	0.9	1.1	11.5	10.8	6.3	17.0	10.4	70.8	108.7	–	–
10.79	14.2	25.0	–0.3	0.9	1.2	12.0	10.2	6.5	17.2	11.0	76.0	111.0	–	–
28.00	–	–	9.5	34.7	–	–	–	–	–	–	–	–	–	–
33.00	–	–	43.8	167.2	–	–	–	–	–	–	–	–	–	–

Note: *S, P, D,* |*S*|, |*P*|, |*D*| and |*P* – *S*| are given in 10^{-10} mA^{-1}

for p-GaP. *S* coefficient of p-Ge appeared before in [2,3,6] and *D* values of n-GaP in [4]. All other values are new.

Conclusions

Using *D*, *S* and *P* values from Table 2 and equation (5) or (6) the responsivity of a photon drag optical rectification detector made out of p-Ge, p-Si, p-GaAs or n-GaP orientated at any direction can be found. By using |*P*|, |*S*|, |*D*| and |*P* – *S*| values for p-GaP the responsivity of detectors orientated along specific directions in the 2.6 to 3 μm or 9-11 μm range can also be found.

It can be seen from Fig. 2 that p-Ge is a high response photon drag detector in the 2 to 11 μm range. Unfortunately, it is very sensitive to wavelength variation and therefore cannot be used as a reliable detector for power measurement over the whole range. n-GaP has slightly lower responsivity in the 10.6 μm range but is a better detector from 2 to 8 μm. The ratio of maximum and minimum responsivity in the 2 to 11 μm range is 20/1.5. p-GaP is quite a good detector in the 10.6 μm range but is worse in the 2-3 μm range. p-GaAs is less sensitive than n-GaP but the maximum to minimum signal ratio is better than that of n-GaP, about 1.3/0.3. Finally p-silicon has rather lower response than p-GaAs from 2 to 5 μm and 10.6 μm but is obviously a far better detector at 28 and 33 μm. A more detailed publication on p-silicon photon drag detectors is appearing elsewhere.[7]

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