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Competition between sub-bandgap linear detection and degenerate two-photon absorption in gallium arsenide photodiodes

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Summary

We investigate the response of a GaAs PIN diode to sub-bandgap photons. We evidence and describe two regimes: a regime of degenerate two-photon absorption, with a quadratic dependence to the incident flux, and a sub-bandgap temperature dependant linear regime, described as a photo-assisted Shockley Read Hall effect.

Introduction

Room temperature infrared quantum detection is still a challenge today. Indeed, the low bandgap semiconductors used to achieve direct infrared detection suffer from an important dark current related noise. This issue is usually solved by cooling down the material to cryogenic temperature thus reducing the thermal agitation. We propose to investigate a strategy to mitigate this problem by making use of two-photon absorption inside wide gap semiconductors from the visible sector such as GaAs and InP.

Infrared detection through two photon absorption processes implies the detection of low optical fluxes delivered by CW sources, which proves to be quite challenging. Indeed in the low flux regime, a linear dependence of the photocurrent to the subbandgap light intensity has been previously observed in silicon devices clearly showing that another photocurrent generation process can prevail over the two photon photocurrent (TPC). This process called photo-assisted Shockley-Read-Hall (PASRH) has been described in silicon [1].

We observe and investigate the competition between those two processes in a commercial GaAs PIN diode at 1.55μ m at very low flux for two temperatures. We also study the transitions for various temporal regimes from ns to μ s allowing to determine the two-photon absorption coefficient and the trap densities in the photodiode material.

Competition between two transition processes

The experimental set-up consists of a pulsed light source focused on a commercial GaAs PIN photodiode. We acquire the current *vs* incident power characteristics represented in Fig.1a. Two distinct regimes can be clearly identified : the quadratic regime above 1 mW of average incident optical power and a linear behaviour below 100 μ W. Moreover, as shown by the current *vs* incident power characteristic on Fig.1b, the linear regime disappears when the diode is cooled down to cryogenic temperature.

The quadratic regime is characteristic of TPC. It is a third order non-linear process which can be described as the quasi simultaneous absorption of a pair of photons as shown on the inset of Fig.1b. Indeed, TPC in semiconductors using sub-bandgap photons can be modeled by a two-step process: a photon of energy $E < E_g$ can promote an electron from the valence band to a virtual state (meaning a non stationary state) in the gap. During the lifetime of this state (given by the second Heisenberg principle $\Delta \tau \geq \frac{\hbar}{2(E_g - E)}$), a second photon carrying enough energy can complete the



Fig 1. (a) current *vs* incident power characteristic of the GaAs diode illuminated by a 10ns pulsed laser at 150kHz repetition rate and 1.55 μ m. Two regimes are visible: a linear behavior at low flux regime (slope=1, preponderance of PASRH), a quadratic behavior at higher flux (slope=2, preponderance of TPC) (b)I-P characteristic of the detector at two temperatures. The linear regime disappears at 80K.

transition, hence creating an electron-hole pair and generating a photocurrent, namely a two-photon current. The very short lifetime of this intermediate state in visible gap material (in the fs range) is responsible for the intrinsically low efficiency of this process, as it requires the quasi simultaneous occurrence of two photons in this time interval.

The linear regime has been previously observed in silicon devices and has been described as a photo-assisted Shockley-Read-Hall (PASRH) effect. It is based on the ionization of traps from deep levels in the bandgap to the conduction band. Those deep levels are delocalized real states, meaning that they can be reached at any time by any photon, thus leading to an appreciable efficiency for the process. The inset of Fig.2b schematically represent the transition.

We model the total photocurrent as the sum of both contributions in order to derive their respective parameters: the two-photon absorption coefficient β and the the quantum efficiency of the PASRH η .

$$< J_{phot} > = < J_{1ph} > + < J_{2ph} > = K_{1ph} < P_{opt} > + K_{2ph} < P_{opt} >^{2}$$
 (1)

$$\beta = \frac{2h\nu}{e} \frac{S}{L} \frac{\langle J_{2ph} \rangle / R_c}{\langle \langle P_{opt} \rangle / R_c \rangle^2} = \frac{2h\nu}{e} \frac{S}{L} K_{2ph} R_c , \quad \eta = \frac{h\nu}{e} \frac{\langle J_{1ph} \rangle}{\langle P_{opt} \rangle} = \frac{h\nu}{e} K_{1ph}$$
(2)

We derived from our measurements the values of β = 65.1 \pm 1.7 cm/GW and η = [6.1 \pm 0.6].10^{-8}

Conclusion

To windup, we observe that a real competition appears in terms of photocurrent generation in our device, dramatically limiting the capability to detect subbandgap photon pairs at low optical powers. Nevertheless, several strategies are accessible to allow a clear predomination of the TPC signal: on one hand, PASRH level could be decreased, either by cooling the detector[1] or improving the active medium quality in term of volumic trap density. On the other hand, TPC could be increased through enhancing the non-linear process thanks to adequate devices, such as resonant nanostructures[2] or quantum wells.

References

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