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Review

Near-room temperature MWIR HgCdTe photodiodes limited by vacancies and dislocations related to Shockley–Read–Hall centres

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ABSTRACT

Trap assisted tunnelling via traps located at dislocation cores as well as mercury vacancies are considered as the mechanisms of enhanced thermal generation of charge carriers in reverse-biased MWIR HgCdTe photodiodes operating with Peltier cooling. Field-induced reduction of trap activation energies increases thermal generation and creates conditions for large tunnelling currents. The model for LWIR devices published previously in Ref. [20], also explain experimental current–voltage characteristics of the MWIR photodiodes assuming great misfit dislocation density at graded gap interfaces between absorber and contact regions.

Contents

1. Introduction

An ultimate goal for infrared photodetectors is the perfect, quantum noise limited performance at ambient temperature. Significant progress has been achieved with the use of heterostructure design of the devices [1–5] in which the active region, the absorber, is sandwiched between wide gap layers that protect it against parasitic thermal generation at contacts, surfaces and interfaces. The variable gap semiconductor, $Hg_{1-x}Cd_xTe$ (HgCdTe) was and still is the main candidate for the perfect infrared (IR) detectors. Due to small changes in lattice constant, the material can be used for band gap engineered devices. Practical HgCdTe heterostructures for the devices have been grown with advanced epitaxial techniques such as MBE [6] and MOCVD [7].

Despite recent technology improvements, the performance of practical uncooled devices still remains below the fundamental limits [5]. This is due to the excess charge carrier generation caused by the point and extended defects. The most likely defects are residual metal site vacancies and dislocations [8]. In spite of the weak dependence of lattice constant on composition, the misfit

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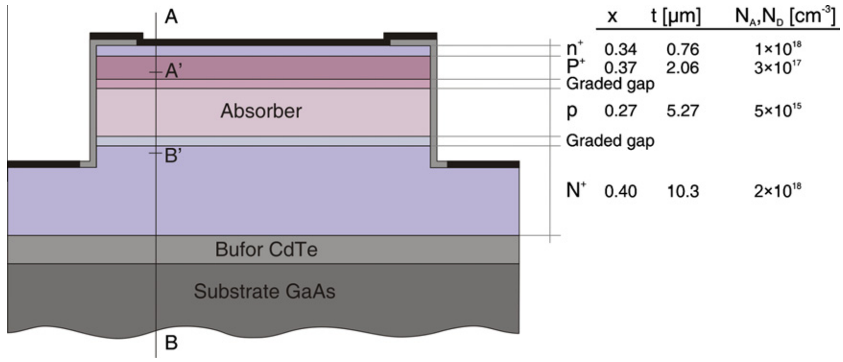

Fig. 1. Design of an HgCdTe heterostructure.

dislocation density can be large at heterojunction formed by regions of different band gap. An extensive literature dedicated to dislocation issues in HgCdTe material [9–13] and their effect on device performance [14–20] has been published.

This paper presents computer simulations of dark current in middle wavelength infrared (MWIR) photodiodes operating at near-room temperatures and experimental data measured on MOCVD grown HgCdTe heterostructures. We used here theoretical model and numerical methods described in our previous papers [18–20]. This computer program solves the system of nonlinear continuity equations for carriers and Poisson equations. In the model ideal diode diffusion, generation–recombination, band-to-band tunnelling, and trap-assisted tunnelling are included as potential limiting mechanisms in the photodiodes. To our knowledge, our paper for the first time considers influence of trap assisted tunnelling (via traps located at dislocation cores) as well as mercury vacancies as the mechanisms of enhanced thermal generation of charge carriers in reverse-biased near-room temperature MWIR HgCdTe photodiodes.

2. Model and assumptions

2.1. Diode structure

Practical MWIR photodiodes were MOCVD grown on CdTe-buffered GaAs substrates [21,22]. Fig. 1 shows the structure of considered HgCdTe photodiode. Basically, the device is a three-layer N^+pP^+ diode with p-type narrow gap absorber and heavily doped heterojunction electron and hole contacts optimized for operation with Peltier cooler (about 240 K). An auxiliary n^+ top layer provides a low resistance contact between the P^+ and anode moralization. The n- and p-type doping was achieved by *in situ* doping with iodine and arsenic during horizontal, near atmospheric pressure MOCVD reactor with H_2 carrier gas. Growth was carried out at temperatures of about 350 °C using the interdiffused multilayer process (IMP) technique onto GaAs substrates of orientated 3° off (1 0 0) towards the nearest (1 1 0). The growth was completed with cooling down procedure at metal rich ambient. No prolonged post growth dopant activation nor stoichiometric anneal was used.

The interfaces between the layers show significant composition and doping grading (Fig. 2). The grading is mostly due to CdTe/HgTe interdiffusion and dopants diffusion that occurs at growth temperature.

2.2. Method of analysis – Brief description (after Ref. [20])

The analysis of photoelectric effects in semiconductor structures requires the solution of a set of transport equations that are comprised of the continuity equations for electrons and holes,

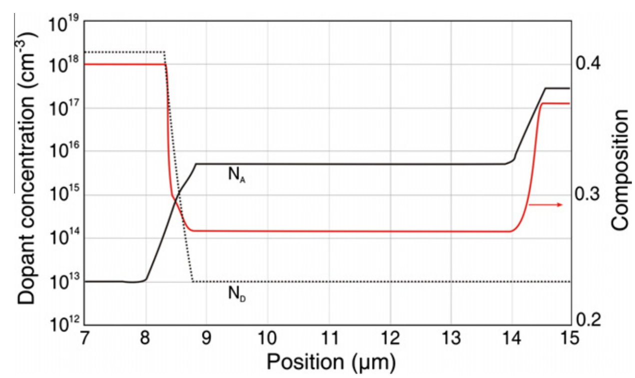

Fig. 2. Approximated composition and doping SIMS profiles along A′ and B′ cross section (Fig. 1) in $a \sim$ 5-μm MOCVD HgCdTe photodiode.

Poisson's equation, and the thermal conductivity equation. The transport equations are given by

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla\vec{j}_h + G - R, \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla\vec{j}_e + G - R, \tag{2}$$

$$\nabla^2\Psi = -\frac{q}{\varepsilon\varepsilon_0}\left[N_D^+ - N_A^- + p - n\right] - \frac{1}{\varepsilon}\nabla\Psi\nabla\varepsilon, \tag{3}$$

$$C_V\frac{\partial T}{\partial t} - H = \nabla\chi\cdot\nabla T, \tag{4}$$

where Ψ is the electrostatic potential, j is the current density, q is the elementary charge, C_v is the specific heat, χ is the thermal conductivity coefficient, T is the temperature, G is the generation rate, R is the recombination rate, and H is the heat generation term. In the last term, a Joule heat is introduced as the heat generation. The indices n and p denote electron and hole concentrations, respectively.

In spite of the fact that the above equations are generally known, their solution represents serious mathematical and numerical problems. The reason for the difficulty is the nonlinearity of these equations where carrier densities, ionized dopant densities as well as G–R factors are all complex functions of the electrostatic potential, Ψ and quasi-Fermi levels, $\Phi_{e,h}$.

The difference G–R is the net generation of electron–hole pairs, and depends on all generation–recombination mechanisms. In this work G–R is defined by

$$G - R = G_{THE} + G_{BTB} + G_{TAT}, \tag{5}$$

where G_{THE} is the net thermal generation rate, G_{BTB} is the net generation due to band-to-band tunnelling, and G_{TAT} is the net generation