Abstract. Low frequency noise spectroscopy (LFNS) is a tool, complementary to other methods, such as deep level transient spectroscopy, to characterize traps in semiconductor devices. LFNS method was described, illustrated and applied to HgCdTe high operating temperature infrared detectors. The fluctuation model which connects generation-recombination process (Lorentzians) with trap level in doped semiconductor was briefly introduced. Several trap levels were obtained for detectors with different band gaps ($E_g$ in the range 219 meV to 320 meV at 300 K). One of the trap levels $E_t \approx 140$ meV, is common for almost all examined specimens. This level, which lies in the middle of the band gap, is the main source of generation–recombination noise observed in examined HgCdTe HOT detectors.

1. Introduction

Low frequency noise in various radiation detectors is a key issue since it introduces detectivity limitation of a biased detector. Low frequency noise could have either $1/f$ or Lorentzian spectrum connected with electrically active defects acted as generation-recombination (g-r) centres (traps). Low frequency noise spectroscopy (LFNS) can be used to identify the traps that contribute to the low frequency limitation of device performance. Moreover, extracted trap parameters can be compared to the values obtained by deep level transient spectroscopy (DLTS), impedance spectroscopy (IS) or optical methods, such as photoluminescence.

LFNS has been successfully applied for studying trap levels in Au/Ni-doped nanowires [1], [2] Ge JFETs [3]. Several publications compare results between DLTS and LFNS [4] [5], [6], [7]. It was shown that extracted trap levels are consistent in both methods. LFNS has some advantages over DLTS, since the latter requires high excitation signal (reverse voltage bias), proper samples with depletion region and with small leakage currents. It is also possible with LFNS to roughly estimate the trap density, when dopant concentration and sample volume are known [8]. This problem vanishes in LFNS because current fluctuations are the source of the information about traps in contrast to DLTS, where capacitance transients are analysed. Nevertheless, there are also some disadvantages because only the traps located near Fermi level can produce g-r noise. It is also necessary to take into account that not all g-r noise comes from the bulk. The g-r noise could be surface [9] or contact layers [10] related. LFNS requires physical model to interpretation of the location and density of the traps. This
leads to the conclusion that LFNS should be considered as a complementary tool to other methods of semiconductor trap characterization [11].

In this work, LFNS is described and applied to high operating temperature (HOT) HgCdTe midwavelength infrared detectors (MWIR) with various band gaps of the absorber. Mercury cadmium telluride is a still basic material for infrared detectors [12]. The trap levels were extracted according to Kleinpenning et al. [13] model which is briefly introduced.

2. Samples and Method

Detectors were grown by Metal Organic Chemical Vapour Deposition on GaAs substrate with CdTe buffer in VIGO System S.A. laboratories. The basic architecture of specimens is presented in figure 1 [14]. The capital letters denote wide band gap material, while “+” sign means high doped region. Generally, the devices are P`P+N+ diodes with lightly p-type narrow gap absorber and heavily doped/wide band gap hole P+ and electron N+ contacts. P-type layers are As doped while N-type layers are I doped. Additional n+ cap layer provides low resistance between metallization and hole contact. The surface is CdTe passivated. Detailed fabrication process was previously reported [15]. Several detectors with slightly different thickness and composition of particular layer were examined. The key difference is the absorber composition which equals $x = 0.321$ (specimens #3, #8), 0.304 (specimen #2), 0.291 (specimen #4), and 0.247 (specimens #1 and #6). It corresponds with the band gaps (estimated at 300 K) $E_g = 320$ meV, 296 meV, 280 meV, and 219 meV, respectively.

Figure 1. The basic architecture of HOT IR detectors described in the paper.

LFNS relies on examination of the temperature dependence of a corner frequency $f_c$ which characterizes a Lorentzian spectrum $S(f) = A[f_c(1+f/f_c)]^2$, contributed by g-r noise, where constant $A$ is connected with noise amplitude. The Lorentzian inclusions appear in the power spectral density of the detector’s noise, $S_f$, for biased detector. The total measured noise usually includes g-r noise, $1/f$ noise and white noise (shot, thermal noise or system noise). Then, the product $f \cdot S_f$ could be written in the form

$$f \cdot S_f = fA[f_c(1+f/f_c)]^2 + B + f \times C$$

(1)
where $B$ is the intensity of $1/f$ noise at 1 Hz and $C$ is the white noise therm. Equation (1) is depicted in figure 2 (a), where the frequency dependence of the particular contributions is shown. It is convenient to analyse the product $f \cdot S_i$ because the local maxima of the Lorentzians appear at frequency $f = f_c$ on the flat noise background constituted by $1/f$ noise. The corner frequency follows a thermally activated manner

$$f_c = f_0 \exp(-E_A / kT)$$

(2)

where $E_A$ is an activation energy of the g-r process and $f_0$ is a constant. The activation energy can be easily extracted from a set of plots, $f \cdot S_i(T)$, because the local maximum changes the position with temperature. This is illustrated in figure 2 (b), where measured products, $f \cdot S_i(T)$, are shown at different temperatures for biased specimen MCT #8. It is clearly to see that the local maximum, which initially appears at $f = 10$ Hz ($T = 145.8$ K), changes the position with temperature.

![Figure 2](image_url)

**Figure 2.** (a) The sketch of the product $f \cdot S_i$ with typical noise contributions. (b) The measured products $f \cdot S_i$ versus temperature for the specimen #8 at -50 mV.

The Arrhenius plot of the corner frequency from figure 2 (b) is illustrated in figure 3. Fitting procedure with equation (2) shows that the fluctuation (g-r) process has the activation energy $E_A = 235$ meV.
3. Results and Discussion

The connection of activation energies with a trap level requires a model of g-r process, which occurs in semiconductor material. A few authors developed such a model which helps to interpret the LFNS results in the context of trap parameters such as a trap level $E_t$, a capture cross-section $\sigma$ or a trap the density $N_t$. Kleinpenning et al. [13] considered g-r noise in n-type GaAs layers. For electron trap level, where density of free electron $n$ is larger than the density of trapped electron $n_t$ and the Fermi level $E_f$ lies below $E_t$ by a few $kT$ ($|E_t - E_f| >> kT$ – energy is measured up from valence band), the corner frequency can be expressed as [13]:

$$f_c = \frac{1}{2\pi} v_{th} \sigma N_c \exp(-|E_t|/kT)$$

(3)

where $v_{th}$ is the thermal velocity, $N_c$ is the effective density of states in conduction band and $\sigma$ is the capture cross section. Scholz et al. developed similar expression [5] which was successfully adopted for GaN MOSFETs studies [7]. The temperature dependence of $v_{th}\sigma N_c$ should be considered. Typically, $T$-dependence of $v_{th}N_c$ is $T^2$ [11]. The temperature dependence of a capture cross section is a separate problem, because it could also follow a thermally activated manner $\sigma = \sigma_0 \exp(-E_\sigma/kT)$. This kind of behaviour was observed for DX centres in AlGaAs layers [6]. Using LFNS, it is not possible to obtain the activation energies $E_\sigma$ and $E_t$ separately, contrarily to DLTS, where $E_\sigma$ could be extracted. The assumption about position of Fermi level with the respect of the trap level could be satisfied due to the existence of band bending in the deletion layer even in high doped material. It is postulated by Kleinpenning et al. [11] who observed g-r noise in high doped n-GaAs where Fermi level lies well above trap level.

LFNS was performed for several HOT IR HgCdTe detectors in the temperature range 65 K - 300 K. The values of activation energies and trap levels, obtained for fluctuations processes in particular specimens, are gathered in Table 1. It is assumed that in lightly p-doped absorber the hole trap plays a major role. Consequently, equation (3) for the hole trap, can be rewritten in the form $f_c = 1/2\pi v_{th} \sigma N_v \exp(-|E_v|/kT)$, where $N_v$ is effective density of states in valence band. The trap level was obtained using above equation and assuming that $T$ – dependence of thermal velocity and effective density of states in valence band is $T^2$. 

Figure 3. The Arrhenius plot of the corner frequency from figure 2 (b). The solid line indicates the activation energy $E_A = 235$ meV.
Table 1. The activation energies and trap energies of fluctuation processes obtained by LFNS for HOT HgCdTe detectors.

| Specimen | Activation energy [meV] | Trap level [meV] |
|----------|-------------------------|------------------|
| MCT#1    | 30, 110                 | 15, 90           |
| MCT#6    | 155, 180                | 140, 165         |
| MCT#2    | 80, 155                 | 60, 135          |
| MCT#4    | 140                     | 130              |
| MCT#3    | 155                     | 140              |
| MCT#8    | 40, 110, 155, 235       | 35, 90, 140, 210 |

One can notice that the trap level \( E_t \approx 140 \) meV is detected for almost all detectors specimens including devices with the narrow (specimen #6) and the wide band gap absorber (specimens #2, #3, #4, #8). This level is responsible for g-r noise and is common in our HgCdTe specimens. Similar trap level was reported by Hu et al. [16] with the use of of admittance spectroscopy.

4. Conclusions

Low frequency noise spectroscopy is a powerful method to characterize traps in semiconductor devices, complementary to optical and other electrical methods such as deep level transient spectroscopy or admittance spectroscopy. LFNS is sensitive and easy to apply but interpretation of the results could be a difficult task because the Lorentzian inclusions, appearing in the spectrum, could have various origins related to, e.g., surface and contacts. LFNS requires a model of generation-recombination processes occurring in semiconductor to extract the position of trap levels. However, LFNS results support DLTS results in many studies. LFNS performed on HOT HgCdTe detectors with various absorber band gap reveals a common trap level \( E_t \approx 140 \) meV (probably hole trap) which lies in the middle of the band gap.

5. References

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Acknowledgement
The work was supported by the Polish research supporting agencies National Science Centre (NCN), under Project No. DEC-2014/13/N/ST7/03074 (Ł.C.), and The Polish Ministry of Science and Higher Education under Key Project No. POIG.01.03.01-14-016/08.