

Optoelectronic properties of GaP photodetector in an IR converter cell

H. Y. KURT*

Physics Department, Faculty of Science, Gazi University, 06500 Ankara, Turkey

The complicated structure of photodetectors, which enable to convert *IR* radiation to the *VIS* one has not been clarified with all aspects; in fact, the use of different semiconductors and the effects of different plasma parameters to the *IR* enhancement and hysteresis phenomena has not been understood, yet. Within this context, the optoelectronic properties of a gallium phosphate (*GaP*) photodetector were experimentally explored in the *IR* image converter cell. It was observed that *GaP* material exhibits various interesting behaviors, when the applied voltage is increased gradually. The discharge current I changes at different illumination intensities, when an external *IR* light source was used. Moreover, the tail region of the absorption spectrum of *GaP* played an important role to characterize current under various illuminations L_n . It was proven in the sweep up/down voltage tests that a clear hysteresis behavior persists for a wide voltage range. This feature makes this photodetector been a good candidate for the semiconductor memory studies and strictly related to negative differential resistance (*NDR*). In addition, the effects of plasma parameters such as the gas pressure p and the interelectrode distance d were also explored in detail for the first time and it was found that p affects the hysteresis behavior dominantly in the converter.

(Received August 11, 2012; accepted March 13, 2014)

Keywords: Semi-insulating GaP photodetector, Hysteresis, Plasma, IR image converter, Discharge Light Emission

1. Introduction

Gallium phosphate (*GaP*), is an important photodetector material and has been used a wide-band-gap semiconductor, making it a good candidate for optoelectronic device application at room-temperature [1]. It is often used as a substrate for quantum devices and optoelectronic devices [2]. Since it is among *III-V* materials, it finds place for optoelectronic studies in addition to the usage in active photonic devices. *GaP* has also attracted attention as a *WBG* material for *LEDs* operating in the blue-to-ultraviolet region [3,4]. In this manner, *GaP* exhibit high spectral response in the wavelength range from 400 to 500 nm [5]. For instance, the production of high-frequency and high-power microwave components is among the important application areas [6]. It has been known that *GaP* is better than the *GaAs* and pure *Si* materials in microwave power with respect to its trap concentration [7]. Therefore, many explorations have been realized in this direction over the last decade. It is certain from the literature that the *NDR* affects the feature of microwave devices [7]. In this manner, *NDR* formation was successfully included in many semiconductor devices. For instance, Gunn diodes are common in microwave and millimetre wave signal applications in that context. The previous experimental study have proven that some conditions should be ascertained in order to observe *NDR*: There exist upper and lower satellite valleys in the band structure [8-9]. The charge carriers can be excited with certain mobility near to the lower valley in conduction band [9]. In fact, the carrier mobility in the valley can be much lower than in the other

one. The second important condition for *NDR* is that the energy difference between the upper and lower satellite valleys should be larger than $k_B T$ (T is operation temperature). However, this difference should not be larger than the band gap. It will be proven that all these conditions are valid for *GaP*. In addition, *GaP* indicates hysteresis behaviour, when the applied voltage is swept up/down. Such a hysteresis effect has not been fully-understood since it also depends on the plasma parameters of the converter. Meanwhile, such an effect can be explained by bistable potential well inside the gas discharge device.

This paper reports the effect of plasma-semiconductor interaction in terms of *NDR* and hysteresis phenomena beyond certain applied voltage U . Moreover, the electrical and optical characterization of the undoped *SI* bulk *GaP* photodetector is handled. *GaP* is found to be exhibit *IR* sensitivity in the near infrared region of the spectrum [10-12]. Qi-Xian Zhang *et al* [10] have found that the tail of the *UV-vis* absorption spectrum of *GaP* at room temperature that extends out to about 800 nm is resulted from the intrinsic impurities or defects in *GaP* [13]. This poor sensitivity at the spectral tail has not been explored in an *IR* image converter before. One of the important results of the present work is to demonstrate the above mentioned *IR* photoconductivity of *GaP*. However, its application as an *IR* photodetector in this structure is restricted for some gas discharge parameters.

The present study also includes the optoelectronic properties of *GaP* photodetector at different illumination intensities and pressures. It covers the hysteresis phenomena at different rates. It is the first time that this

phenomenon has been encountered in *GaP* in the *IR* converter cell. The paper is organized as follows: The experimental details are given in Sec II. The results and corresponding discussion are presented in Sec III. The conclusions are given in the last section.

The paper is organized as follows: In Sec. II, the experimental setup and some measurement tools are introduced. The main results and discussion are given in the next section. Finally, the conclusions part includes the important remarks on the observations.

2. Experimental

The experimental set-up for the test of optoelectronic features of *GaP* is schematically represented in Fig. 1. A *dc* voltage up to 2000 Volt is applied to the cell and photomultiplier tube is used to record the intensity value of *DLE*. A Stanford (*PS 325*, 2500V-25 W) is used as a digital high power supply and the measurements are taken via connection it to the computer for data acquisition in *IR* image converter cell.

Insulating mica foil is placed between *GaP* cathode and anode as an active discharge gap and the interelectrode distance. The gap spacing and the diameter of the *GaP* photodetector are kept constant at 240 mm and 22 mm respectively, and voltage values between 200 and 2500V are adjusted to initiate the gas discharge. The preparation of the specimen is out of our scope since the specimen was provided from a company (for details on the preparation of the specimen please refer to [14]). Ohmic contact to *n*-type *GaP* photodetector is obtained by evaporating a transparent film of *Au* at about 350 °C with the thickness of 40nm.

The range of pressure is adjusted from 28 Torr to 690 Torr during the experiments. The discharge current is measured using a Digital Multimeter (Keithley 199) through a 10 k Ω resistor connected in series to *IR* converter cell. The cell is directly connected to a rotary pump in order to adjust pressure. Gas discharge gap is located between the *GaP* photodetector and a glass disc. At the same time, gas discharge is created between these two electrodes. Current–voltage characteristics of the *GaP* photodetectors are measured at room temperature.

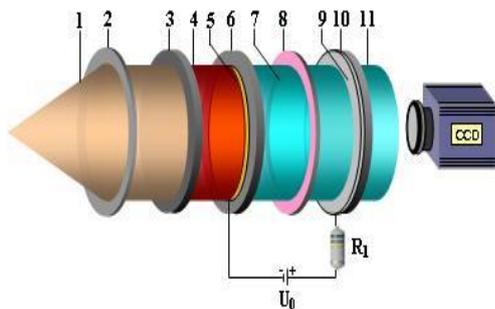


Fig. 1. 1-incident light beam; 2- lens; 3-Si filter; 4- *IR* light beam; 5-semitransparent *Au*-layer; 6-*GaP* photodetector; 7-gas discharge gap; 8-mica foil; 9-transparent conductive *SnO₂* contact; 10-flat glass disc; 11- UV- visible light beam.

The setup of the convertor is presented in Fig. 2. In the experiments, the *CVCs* are recorded for increasing and decreasing voltages (i.e. here we use step up/down term for this process) within a rate of 5 Vs⁻¹[15]. The electrical current flowing in the cell from anode to cathode and the voltage *U* are measured synchronously by a Keithley 199 multimeter and a Stanford *PS 325* type voltage supply. Current is measured by dividing the voltage by the load resistance of 10 k Ω , which is attached series to cell. The stability of the gas discharge is investigated for various interelectrode distances *d*. The measurements are digitalized via custom-made software. The *DLE* can be obtained by a photon counting mechanism (ELSEC 9010). In order to excite the material optically, the system can be irradiated by different external *IR* light. Thus different electronic states of *GaP* can be examined. For this aim, the photocathode can be illuminated by a lamp with 250 W in front of the cathode by changing the photoconductivity of the sample. The illumination intensity *L_n* can be varied between 10⁻⁶ Wcm⁻² and 10⁻² Wcm⁻² by the use of various filters, which are positioned in front of the lamp.

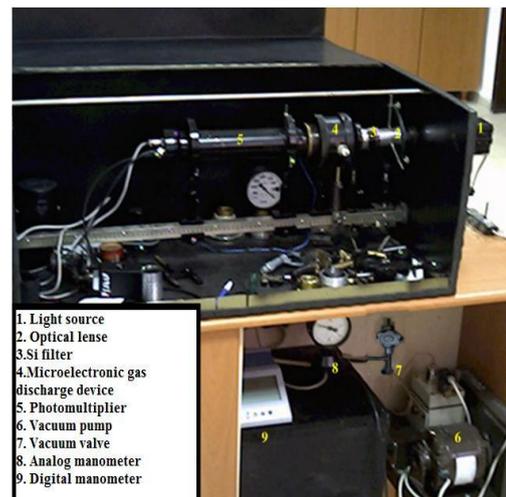


Fig. 2. A photo of converter with measurement setup. The main part of the system is the discharge cell given by No. 4 (Fig. 1).

3. Results and discussion

Due to the indirect gap material, high breakdown voltage is needed to initiate the discharge in the *IR* converter cell. The effects of the illumination and pressure on the current-voltage characteristics (*CVCs*) are presented in Fig. 3 (a-c). Fig 3(a-c) shows the pressure dependencies of the *GaP* photodetector as a function of illumination intensity. In accordance to the results obtained different pressure regime, *IR* sensitivity of the system can be distinguished.

When *GaP* photodetector was exposed to an *IR* light, the current in the system increased due to the carrier generation in the structure. It is obviously seen from Fig. 3(a-c) that *IR* photosensitivity is strongly influenced by the pressure change for *p* = 160 Torr and *IR* illumination provokes the three types of conductivity in the system.

However, for other pressure regimes (i.e., $p = 220$ and 290 Torr), there is an overlap of three conductivity for different IR irradiation. From Fig. 3(a-c), it can be seen that the curves are adjacent to the each other. In addition to the current measurements, *DLE* measurements are carried out. Experimental measurements of *DLE* show the same behavior with the current in Fig 4(a-c). But, we can conclude that *DLE* is much more sensitive to the IR irradiation if one compares with current. That is; optic measurements indicate much sensitive IR photo response.

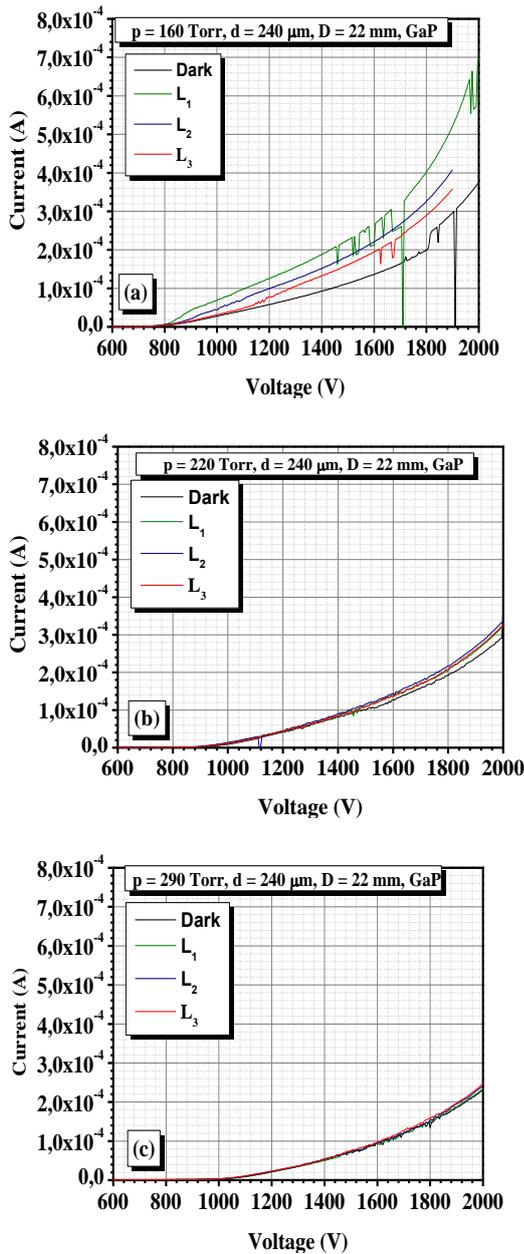


Fig. 3(a-c). CVCs of IR converter cell respect to the pressure in darkness and under a weak L_1 and strong illumination intensities of and L_3 , respectively. The moderate illumination is denoted by L_2 .

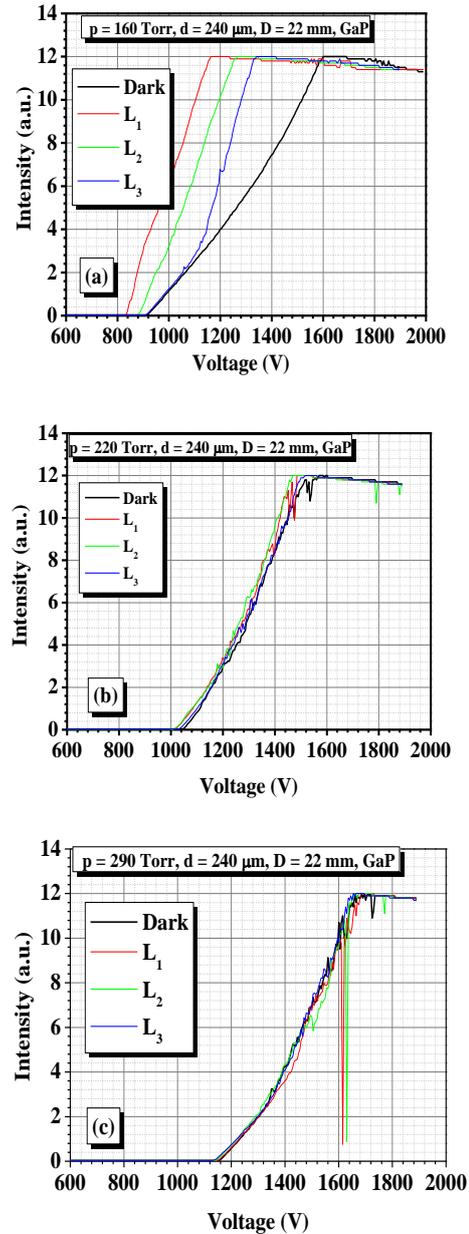


Fig. 4(a-c). DLEs of IR converter cell respect to the pressure in darkness and under a weak L_1 and strong illumination intensities of light L_3 , respectively. The moderate illumination is denoted by L_2 .

For certain pressure ranges, the electrons of gas molecules are excited, thus it yields to vary the values of current as functions of photon numbers. Since the photon numbers depends on the intensity of light source when the number of electrons increase the difference between the *DLE* differs from each other. For a certain pressure range, photons find maximal electron numbers to excite and make a current loop between cathode and anode, thus the current differs as function of light illumination. However, in the cases of lower and higher pressure rates photons cannot excite sufficient numbers of electrons in order to deviate from the dark case and the resistance of gas media

does not allow excited electrons to complete the discharge currents, respectively [16].

In fact, for higher pressures electrons cannot reach anode easily in an intense gas media. As shown in Fig. 5, the *IR* response of the system that can be observed clearly inside of the Negative Differential Resistance (*NDR*). It should be noted that there is no *IR* response up to the *NDR* region in the system [17-19]. But, *IR* conductivity enhancement is observed due to the charge storage center effects in this region.

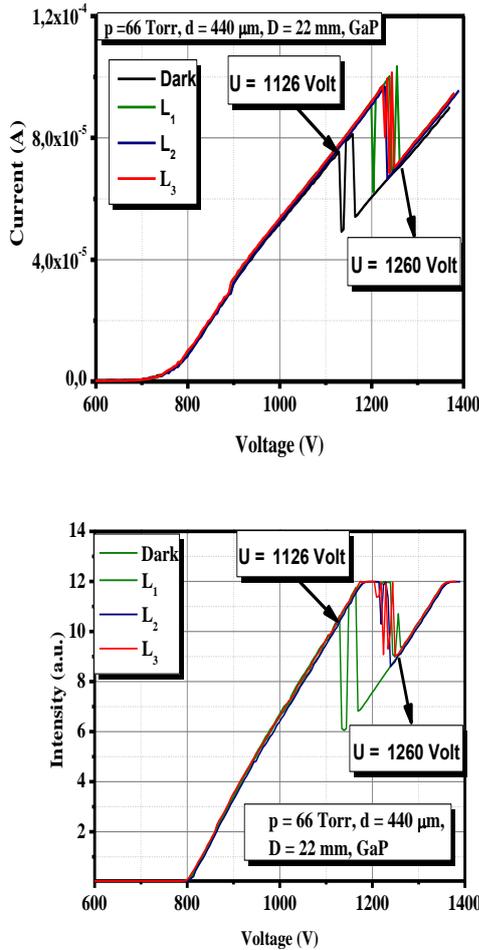


Fig. 5. CVCs and DLEs with N-shaped behaviour for IR converter cell with GaP photodetector in darkness and under a weak L_1 and strong illumination intensities of light L_2, L_3 , respectively. System parameters $p = 66$ Torr, $D = 22$ mm, $d = 440$ μ m.

From our experimental result we can judge that intrinsic impurities or defects in *GaP* have influence upon the *IR* conductivity. The active charges are accumulated on the *EL2* defects being in semiconductor surface [17-19]. The experimental results are in good agreement with other independent authors studying in different systems.

Our experimental results indicate that *IR* conductivity is unaffected by change of illumination intensity in the voltage range investigated up to 1126 Volt. When the *GaP* photodetector was exposed to *IR* illumination, the current and *DLE* in the *IR* converter cell has increased in the range

of between 1126 Volt and 1260 Volt; in other words in the negative resistance region. Beyond this voltage range, there is no difference shown a response to *IR* light.

The *CVC* measurements are performed in order to explore the effects of pressure on the hysteresis in Fig. 6. Under the influence of forward and backward applied voltage, the high hysteresis window is obtained for current. This effect is attributed to the stimulation of *EL2* center under exposure *IR* light. However, to our knowledge, there is no experimental study of hysteresis behavior in *GaP* under different illumination regime. As observed, a relatively slight change at pressure from 160 to 220 Torr, leads to a large change of hysteresis width.

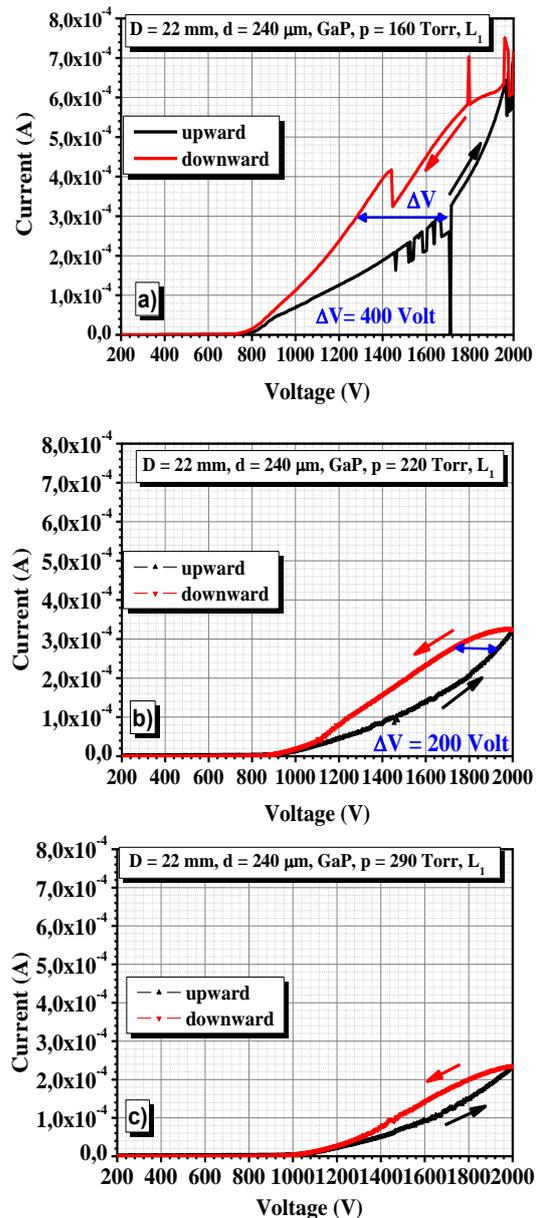


Fig. 6(a-c). Pressure dependence of the hysteresis behaviour for IR converter cell with GaP photodetector under forward increase and reverse decrease of feeding voltage on the system when the GaP photodetector exposed to weak illumination intensity L_1 . System parameters $d = 240$ μ m, $D = 22$ mm.

It is known that electron trap levels on the *GaP* surface have different effects on discharge currents in the cases of forward and backward applied voltage variations. In this manner, surface charge has a considerable influence on the carrier transport. For instance, an earlier study reports the surface states of *GaAs* capturing electrons [20]. According to another study, the hysteresis loop is conducted not only by intrinsic properties of material but also by extrinsic factors [21]. In our study, hysteresis curves are recognized as a result of nonequilibrium process [22]. Strictly speaking, this loop is attributed to an electron capture process and emission from *EL2* deep center if the photodetector is exposed to forward and backward feeding voltage [23]. However, the plasma dynamics also plays an important role for this hysteresis behavior since pressure drop in the cell leads to wider hysteresis window is explored.

From our experiments, the memory window width ΔV is found to be near 400 V at $p = 160$ Torr; 200 Volt at $p = 220$ Torr. According to above results, it can be clarified that the observed hysteresis loops have characteristics of width ΔV for certain pressures and plasma behavior affects the hysteresis in addition to the electron capture processes as believed literature.

Comparing our results with other researches in the literature, the effect of *IR* illumination in such a converter system with *GaP* has not been studied before. However, there are only a few studies on the *IR* transmission spectra as optical features of the material [10, 24]. These recent researches have been taken from either thin film or nanoparticle states of *GaP*. On the other hand, most of the works handled with the transmission features in *UV* or *VIS* regions [25]. But there is not any measurement on the high resistivity planar *GaP* specimen in terms of *IR* sensitivity.

4. Conclusion

In this study, we have investigated optoelectronic properties of *GaP* photodetector in *IR* image converter cell for the first time. Being different from the other studies about *GaP* photodetector, the *IR* sensitivity is explored for different discharge parameter under the influence of an external voltage and illumination intensities. In addition, the hysteresis behavior of the converter was explored in detail. The influence of the illumination and pressure variations on the converter cannot be negligible; in fact they can change the optical properties dominantly. According to the results, the plasma processes inside the discharge cell are found to be dominant, since the hysteresis loop features change at low pressures. Thus it is proven that the conventional belief on the effect of electron capture mechanism on hysteresis is not the unique reason for the hysteresis behavior. In fact, plasma media cannot be neglected. It has also been observed that the

device indicates the negative differential resistance *NDR*, which makes the converter as a microwave component for an additional application. Thus the reported properties of *GaP* can contribute to the manufacture of high frequency microwave devices and *IR*-detection systems in addition to the *UV* and *VIS* spectral region applications.

Acknowledgements

This work was supported by Gazi University BAP research projects 05/2012-47, 05/2012-72.

References

- [1] Z. Q. Xian, W. W. Sheng, R. F. Ping, Chinese Phys. B. **20**, 047802 (2011).
- [2] Z. G. Liu, Y. J. Bai, D. L. Cui, X. P. Hao, L. M. Wang, Q. L. Wang, X. G. Xu, J. Cryst. Growth. **242**, 486 (2002).
- [3] Z. G. Chen, L. Cheng, Gao Q. M. Lu, J. Zou, Nanotechnology. **21**, 375701 (2010).
- [4] O. L. Muskens, S. L. Diedenhofen, B. C. Kaas, R. E. Algra, E. Bakkers, J. G. Rivas, A. Lagendijk, Nano Lett. **9**, 930 (2009).
- [5] D. McIntosh, Q. G. Zhou, F. J. Lara, J. Landers, J. C. Campbell, IEEE Photon. Tech. Lett. **23**, 878 (2011).
- [6] O. Noblanc, C. Arnodo, C. Dua, E. Chartier, C. Brylinski, Mater. Sci. Forum. **338**, 1247 (2000).
- [7] V. V. Buniatyan, V. M. Aroutiounian, J. Phys. D: Appl. Phys. **40**, 6355 (2007).
- [8] H. Y. Kurt, Y. Sadiq, B. G. Salamov, Phys. Status. Solidi. A. **205**, 321 (2008).
- [9] B. Chitara, D. S. I. Jebakumar, C. N. R. Rao, S. B. Krupanidhi, Nanotechnology. **20**, 405205 (2009).
- [10] Q. X. Zhang, Z. C. Zhang, B. P. Wang, J. Phys. D: Appl. Phys. **41**, 185403 (2008).
- [11] B. P. Wang, Z. C. Zhang, N. Zhang, Solid State Sciences. **12**, 1188 (2010).
- [12] J. Gao, Q. Zhan, Andrew M. Sarangan, Thin Solid Films. **519**, 5424 (2011).
- [13] Y. Y. Luo, G. T. Duan, G. H. Li, Appl. Phys. Lett. **90**, 201911 (2007).
- [14] H. Y. Kurt, E. Kurt, Elektronika IR Elektrotehnika. **20**, 55 (2014).
- [15] B. G. Salamov, H. Y. Kurt, J. Phys. D: Appl. Phys. **38**, 682 (2005).
- [16] E. Kurt, H. Kurt, U. Bayhan, Central European J. Physics. **7**, 123 (2009).
- [17] A. Inaloz, H. Y. Kurt, E. Koç, B. G. Salamov, Phys. Status. Solidi. A. **206**, 2559 (2009).
- [18] Y. Sadiq, H. (Y) Kurt, A. O. Albarzanji, S. D. Alekperov, B. G. Salamov, Solid-State Electron. **53**, 1009 (2009).

- [19] H. Y. Kurt, A. Inaloz, B. G. Salamov, *Optoelectron. Adv. Mater. Rapid. Comm.* **4**, 205 (2010).
- [20] H. Kurt, S. Çetin, B. G. Salamov, *IEEE Transaction on Plasma Science.* **39**, 4 (2011).
- [21] J.-H. Park, S. H. Yoon, D. Shen, S.-Y. Choe, Y. S. Yoon, M. Park, D.-J. Kim, *J Mater Sci: Mater Electron.* **20**, 366 (2009).
- [22] E. H. Lemus, E. Orgaz, *Rev. Méx. Fis.* **48**, 38 (2002).
- [23] G. Vincent, D. Bois, *J. Appl. Phys.* **53**, 3643(1982).
- [24] F. Liu, Y. J. Song, Q. R. Xing, M. L. Hu, Y. F. Li, C. L. Wang, L. Chai, W. L. Zhang, A. M. Zheltikov, C. Y. Wang, *IEEE Photon. Technol. Lett.* **22**, 814 (2010).
- [25] H. W. Seo, S. Y. Bae, J. Park, H. Yang, M. Kang, S. Kim, J. C. Park, S. Y. Lee, *Appl. Phys. Lett.* **82**, 3752 (2003).

*Corresponding author: hkurt@gazi.edu.tr