The Observations of the *IR* Sensitivity Enhancement, Negative Differential Resistance and Hysteresis in a Microelectronic Gas Discharge Device with *GaP*

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***Abstract*—In this paper, some interesting features of a microelectronic gas discharge device with *GaP* semiconductor are reported. The device is a complicated plasma system with a metal anode and a *GaP* cathode. A discharge occurs in the micro-scaled gap, when a voltage larger than the breakdown value is applied between these electrodes. Since large region of applied voltages are scanned in the microelectronic gas discharge device, both Townsend and glow regimes are clearly observed and a complete electrical and optical responses of the device has been clarified. Following the increase of *U* gradually, different light emission intensities occur as a result of discharge current *I*. An *IR* light source is also used in order to test the *IR* excitation of the microstructure. Although it has been believed that the *GaP* is sensitive to *UV* and visible regions, it has been proven for the first time that the *IR* sensitivity of *GaP* can be enhanced by using microelectronic gas discharge device, when an appropriate parameter set is applied. Moreover, a negative differential resistance regime, which is important for the high frequency microwave applications, has been observed at moderate voltages. In addition to the negative differential resistance regime, certain hysteresis behaviour is also observed in the sweep up/down cases of *U*.**

***Index Terms*—Gas discharge devices, semiconductor devices, semiconductor materials, air gaps, hysteresis.**

I. INTRODUCTION

Gallium phosphide (*GaP*) is one of a *III–V* semiconductors with an indirect wide-band-gap (*WBG*) of 2.26 eV at room temperature and used in many electrical, optical and electronics applications such as luminance diode [1], sensor nanodevices [2], acousto-optical modulator [3] and optical limiter [4]. In the recent studies, *GaP* has been an interesting material due to its allowance to work for terahertz-scale generation and detection via pulsed lasers at 1040 nm [5]. Thus, *GaP* can be used as an emitter to enhance the energy of terahertz pulses with very high pump powers [6]. One of the usage areas of *GaP* is the production of photodetector tubes, because *GaP* avalanche photodiodes (*APDs*) exhibit high responsivity in the wavelength range from 400 to 500 nm [7]. From the gas discharge field, it is clear that there are two modes of a gas discharge, namely Townsend (*TD*) and glow (*GD*) [8]. The *TD* refers to a weak discharge with a low space charge production (i.e. current). The applied electric field is not deteriorated and the maximum discharge light emission *DLE* radiated from the excited species is found near the metal anode [9]. On the other hand, the *GD* has a stronger discharge mechanism with a higher space charge production [10]. A swarm of positive charge is accumulated about the cathode forming a cathode fall. This is observed as a highly illuminated layer near the semiconductor cathode. The *TD* is ignited at very low currents [10], whereas *GD* is ignited at higher currents. Discharge gap *d*, electrode structure, filled gas type and pressure are key parameters to characterize the discharges. In most of the studies, the applied voltage is almost indistinguishable from the breakdown voltage U_B. In *TD*, a large number of electrons create the current before the breakdown [11]. The electrons can be produced via the associative ionization [11], the desorption from barriers or the electron emission from metastable species [12]. Both theoretical and experimental findings prove that the applied voltage *U*, which enables to produce a current between the electrodes, is called as the breakdown voltage U_B and the Paschen curve can be obtained as function of the multiplication of *p* and *d* [11], [13], [14]. An application of a *MGDD* with the *WBG* semiconductors is the manufacturing of microwave components. High-frequency and high-power components are vital for the microwave applications [15]. It has been known that *GaP* is better than the *GaAs* and pure *Si* materials in microwave power with respect to trap concentration [16]. Therefore, intensive

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researches have been realized in this direction over the last decade. It is also known from the literature that the *negative differential resistance* (*NDR*) affects the feature of microwave devices [16]. In this manner, *NDR* formation was successfully included in many semiconductor devices. For instance, Gunn diodes are common in microwave and millimeter wave signal applications in that context [17]. The previous experimental studies [18]–[22] have proven that some conditions should be ascertained in order to observe *NDR*: There should be upper satellite valleys near to the lower valley in conduction band, where the carriers can be excited with certain mobility [22]. In fact, the carrier mobility in this valley can be much lower than in the other one. The second important condition is that the energy difference between the upper satellite valleys and the lower one should be larger than k_BT. Here T should be the device operation temperature. However, this difference should not be larger than the band gap. It will be shown that all these conditions are found to be valid in our high resistivity material *GaP*. In addition, *GaP* semiconductor indicates a hysteresis behavior, when the applied voltage is sweeped up and down. Such a hysteresis effect can be explained by the existence of bistable potential well inside the gas discharge device. In this paper, the main features of gas discharge device operated in the *air* filled micro-cell are explored. The cathode is formed by a *GaP* semiconductor with high resistivity. To our knowledge, it is the first time that *GaP* indicates a clear enhanced sensitivity to external *IR* radiation in such a *MGDD* and also creates an *NDR* beyond a certain applied voltage U. The paper is organized as follows: In Sec. II, a brief explanation of the experimental setup and some measurement properties are presented. The main results and discussion are given in the next section. Finally, the conclusions part includes the important remarks on the observations.

II. EXPERIMENTAL

The experimental set-up of the microelectronic gas discharge device (*MGDD*) is shown in Fig. 1 and Fig. 2.

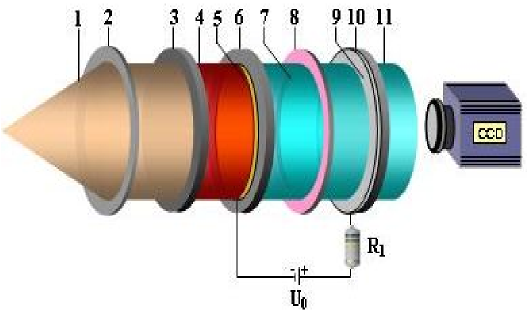


Fig. 1. The microelectronic gas discharge device (*MGDD*): 1) incident light beam; 2) lens; 3) *Si* filter; 4) *IR* light beam; 5) semitransparent *Au*-layer; 6) *GaP* photodetector; 7) gas discharge gap; 8) mica foil; 9) transparent conductive SnO_2 contact; 10) flat glass disc; 11) *UV*-visible light beam.

While Fig. 1 shows only the parts of the discharge device, the total measurement system is shown in Fig. 2. A *d*c voltage up to 2000 Volt is applied to the device, gradually and a photomultiplier tube is used to record the intensity value of discharge light emission (*DLE*). A Stanford (*PS* 325. 2500V–25 W) is used as a digital high power supply. The measurements from the discharge device are received via a connection to the computer. An insulating mica foil is placed between *GaP* cathode and anode in order to form a micro-range *air* gap between the electrodes. A basic circuitry has been formed to measure the discharge current I (see in Fig. 1). The gap spacing d and the diameter D of the *GaP* photodetector can be adjusted to a value between 143 μm and 525 μm and 15 mm and 22 mm, respectively.

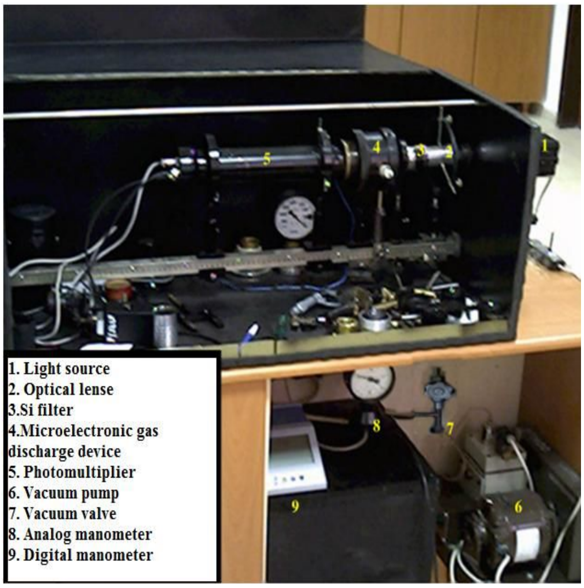


Fig. 2. A photo of *MGDD* with measurement setup.

The voltage values can be sweeped up and down between 200 and 2500V in order to scan the entire plasma regime. Ohmic contact to *n*-type *GaP* photodetector is obtained by evaporating a transparent film of *Au* at about 350 °C. The range of pressure is adjusted from 28 to 690 Torr during the experiments. I is measured using a Digital Multimeter (Keithley 199) through a 10 kΩ resistor connected in series to *MGDD*. Gas discharge gap is located between the *GaP* photodetector and a glass disc (Fig 1). Gas discharge is created between these two electrodes and current–voltage characteristics of the *GaP* cathode has been measured at room temperature. The *CVCs* can be recorded for different voltages with the increasing or decreasing rates of 5 Vs^{-1}.

The photocathode of *MGDD* can be illuminated by an incandescent lamp with 250 W from the front side of semiconducting cathode. By doing so, the cathode photoconductivity is increased up to a certain level. During the experiments, the illumination intensities L_n have been adjusted between 10^{-6} Wcm^{-2} and 10^{-2} Wcm^{-2} by the use of filters.

III. RESULTS AND DISCUSSION

In order to initiate a discharge in the *MGDD*, slightly higher breakdown voltage U_B is required due to the indirect gap feature of *GaP*. Figure 3 shows the so-called Paschen curve (i.e. U_B versus p) for different electrode distances d.

When d gets larger, higher voltages are required for the ignition of the discharge between the electrodes as also stated in previous studies [13], [14]. U_B increases as function of p, however the inclination of this increment decreases with *p*. The discharge current and the light emission (*LE*) intensities under different *IR* illumination intensities are given in Fig. 4(a,b) as function of *U*.

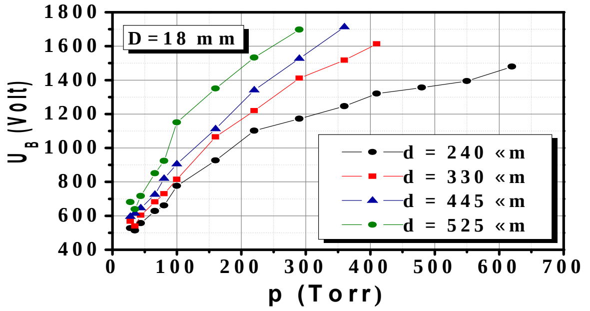
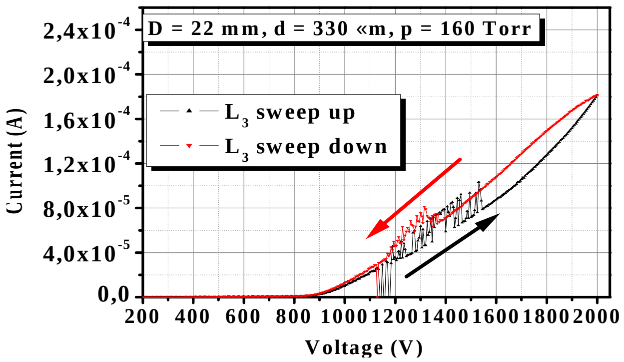
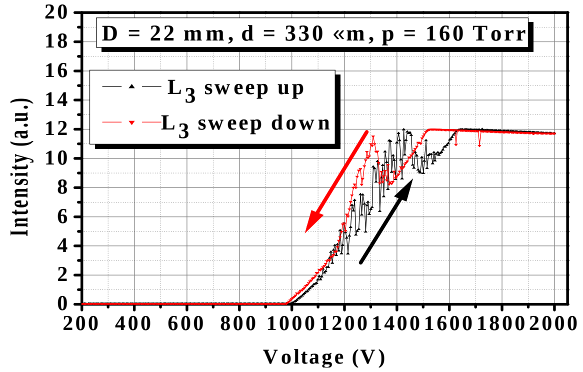


Fig. 3. Paschen curves (i.e. U_B versus *p*) for different electrode distances *d*.



a)



b)

Fig. 4. (a) Discharge current and, (b) light emission (*LE*) intensities in the sweep up/down cases as function of applied voltage *U*. Both graphs prove the hysteresis phenomena and *NDR* in *GaP*.

These plots have sweep up/down cases with a constant ascending or descending step and identify the voltage increase and decrease, gradually. The hysteresis behaviors in two regions are clearly seen from the plots. Therefore, it may be called as double hysteresis loop (*DHL*) and it is the first time that *GaP* indicates such a *DHL* in such a *MGDD*. While *I* values in the right hysteresis loop are larger, the *LE* intensities do not increase too much. In addition, *I* values are lower in the left hysteresis part, however maximal *LE* is almost at the same intensity in this loop. The *DHL* phenomena can be defined as follows: The electrons can have two different bistable mechanisms (i.e. energy levels), which excite different numbers of electrons in *GaP*. The other important feature of Fig. 4(a), Fig. 4(b) is that it contains a *NDR* region beyond *U* = 1300 V. The *NDR* plots can be clearly observed both in *I* and *LE* intensities. Such a behavior is first time observed in *GaP* being in the *MGDD*. Note that the interelectrode distance *d* = 330 μm for these observations. When *d* gets lower than this critique value, such an *NDR* behavior has not been encountered. It should be stated that the observation of *NDR* in *GaP* is very important in the sense that this material can be used as a microwave component in high frequency devices, when an appropriate interelectrode distance is adjusted.

Figure 5 shows the unstable (lower) and stable (upper) discharge currents at two different voltages. In order to produce Fig. 4, the averages of many temporal recordings such as Fig. 5 are used and current averages are defined. While the lower plot fluctuates around $I = 3.5 \times 10^{-5}$ A, the upper one presents much stable appearance with a smooth increment up to $I = 1.18 \times 10^{-4}$ A. Strictly speaking, while the Townsend regime is just below the unstable regime, the glow discharge regime appears at higher currents with high stability beyond the *NDR* region.

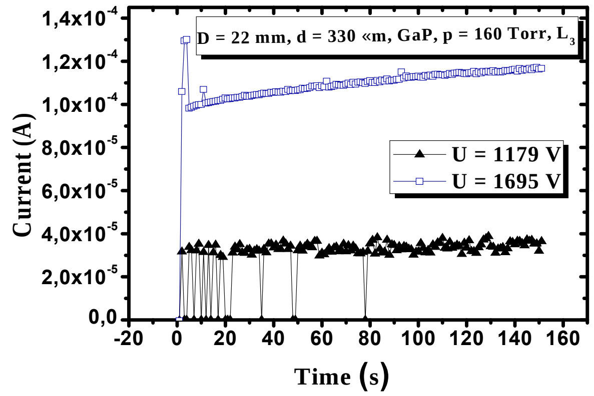


Fig. 5. Discharge currents at two different *U*: The lower (upper) plots are unstable (stable) regimes.

Figure 6 gives two different responses towards three different illumination intensities in cases of two different pressures such as *p* = 35 Torr and *p* = 690 Torr. The *GaP* material is found to be excited optically via an *IR* illumination, when suitable interelectrode distance and pressure are applied.

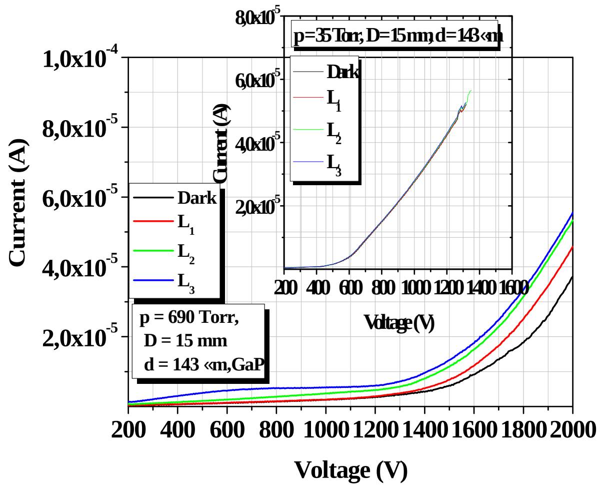


Fig. 6. The current-voltage plots under different external illumination intensities (i.e. dark, weak (L_1), moderate (L_2) and strong (L_3)) at 690 Torr. In the inset graph, the pressure is 35 Torr. All other parameters are same at both graphs. *D* indicates the diameter of *GaP*.

The illumination intensities, which are denoted by L_1, L_2 and L_3 excite the carriers and supply energy to them for higher energy bands. However this process does not only depend on the semiconductor properties, since the gaseous narrow gap media of the *MGDD* also contributes to the carrier dynamics (i.e. current).

By comparing the inset with Fig. 6, the sole parameter change is pressure p. In other words, low pressure rates are much stable towards the external illuminations. The detailed differences between the plots can be summarized as follows: While the illumination intensities (i.e. L_n) cause different currents such as $I = 5 \times 10^{-6}$ A and $I = 10^{-5}$ A for 1400 V at high p, they do not affect the currents such as $I = 6 \times 10^{-6}$ A for the same voltage (i.e. $U = 1400$ V) at low pressures. These current values prove that p is a key parameter for the *IR* excitation of *GaP* specimen.

According to the literature, the effect of *IR* illumination in such a *MGDD* with *GaP* has not been studied before. In fact, there are only a few studies on the *IR* transmission spectra as optical features of the material [4], [23]. These recent measurements have been taken from either thin film or nano-particle states of *GaP*. On the other hand, most of the studies deal with the transmission features in *UV* or visible regions [7]. But there is not any measurement on the high resistivity planar *GaP* material in terms of *IR* sensitivity. According to our findings, if an appropriate pressure rate is adjusted, the optical properties of *GaP* can be enhanced and *IR* sensitivity of the material is increased optically.

IV. CONCLUSIONS

The exploration of an *MGDD* with *GaP* cathode has proven that both the gaseous microdischarge gap and *GaP* semiconductor material dominate the electrical features of the system. The detailed measurements indicate the importance of the charge carriers, which are responsible for the current formation in the system. While the Townsend regime is encountered at 10^{-5} A, the glow regime is observed at 10^{-4} A for this cathode material. The breakdown voltage U_B, which is responsible for the discharge process increases with the interelectrode distance, thereby the discharge can occur at higher voltages. In addition, the other important parameter – pressure affects the optical responses of the discharge system, when the device has been operated under different *IR* illumination intensities for the first time to our knowledge. Strictly speaking, high pressures cause an *IR* enhancement, while low pressures make the system much stable to external illuminations. It has also been observed for the first time that the device indicates the negative differential resistance *NDR* and hysteresis phenomena with *GaP* cathode, when an appropriate parameter set is adjusted. It has been believed that these reported properties of *GaP* can contribute at the manufacturing of high frequency microwave devices and *IR*-detection systems in addition to the *UV* and visible spectral region applications.

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