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TOPICAL COLLECTION: ELECTRONIC MATERIALS FOR RENEWABLE ENERGY APPLICATIONS

Exploration of the Infrared Sensitivity for a ZnSe Electrode of an IR Image Converter

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Significant improvement has been carried out in the field of the II–VI group semiconductor device technology. Semiconductors based on the II–VI group are attractive due to their alternative uses for thermal imaging systems and photonic applications. This study focuses on experimental work on the optical, electrical and structural characterization of an infrared (IR) photodetector zinc selenide (ZnSe). In addition, the IR sensitivity of the ZnSe has primarily been investigated by exploiting the IR responses of the material for various gas pressures, p, and interelectrode distances, d, in the IR converter. The experimental findings include the results of plasma current and plasma discharge emission under various illumination conditions in the IR region. The electron density distributions inside the gas discharge gap have also been simulated in two-dimensional media. Experimentally, the current–voltage, current–time, and discharge light emission plots are produced for a wide experimental parameter range. Consequently, the structural and optical properties have been studied through atomic force microscopy and Fourier-transform infrared spectroscopy techniques to obtain a comprehensive knowledge of the material.

Key words: Gas discharge, plasma, ZnSe photodetector

INTRODUCTION

Semiconductors are vital in many photonic applications. Among them, the photonic switching can be mentioned due to the large third-order nonlinearities. The fundamental studies from the past to the present in that direction are found in the literature, experimentally and theoretically.[1–15] In addition, semiconductors are of interest for a variety of applications such as photodetectors, light-emitting diodes, photovoltaic cells, and transistors. In order to improve the performance of the devices based on the semiconductors, low cost and low power consumption must be provided in the field of optoelectronic materials.

Many materials have been presented in order to provide the development in infrared (IR) detector technology, as in Refs. 18, 19 Especially, in Ref. 19, it is stated that all physical situations in the range of 0.1–1 eV may be designed for IR detectors. Considerable efforts were made to improve IR detector technology in the course of World War II, and all authorities accept that period as the origin of modern IR detector technology. Since then, there has been special focus on IR detectors that can be operated between 3–5 μm and 8–14 μm wavelength of the atmospheric window range, although there has been a growing interest in detector technology, even the far-IR regions finding applications in space research.[20]

The technology based on semiconductors generally deals with narrow bandgap materials such as silicon. However, this cannot be used as an IR photodetector without a cooling unit, which requires heavy and inconvenient auxiliary equipment. Apart from Si-based solar cells, specific long-wavelength applications based on II–VI compounds semiconductor materials such as zinc selenide (ZnSe) is the scope of the present study in realizing an optimal

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response to optical stimulation in the IR region. ZnSe is preferred for its low absorption at IR wavelengths, thereby night-vision devices enable transmissions in the range of 0.5–15 μm. It is also a good material for its high-resolution ability in thermal imaging systems; indeed, it can operate up to 20 μm in that manner. These all make ZnSe an attractive material.[21,22]

The present study analyzes ZnSe for IR sensitivity in an IR converter system. Particular attention has been given to the plasma–semiconductor interaction and underlying electrical and optical characteristics. Since a plasma–semiconductor structure provides low power consumption, a high speed response, and efficient discharge light emission, the micro-discharge plasma cells become important. The structural and optical properties of ZnSe (100) are explored inside the IR converter under various pressures and interelectrode distances. Those analyses have been performed by using atomic force microscopy (AFM) and Fourier-transform IR spectroscopy (FTIR). It will be shown that the optical properties of ZnSe are significantly influenced by the system parameters, i.e. gas pressure and cathode diameter. In addition, electron density distributions along the gas discharge gap have also been theoretically calculated via a simulation study.

EXPERIMENTAL

A parallel plate micro-discharge cell is presented in Fig. 1.[12,13] The experiments have been performed in a vacuum chamber. The anode is made of a transparent SnO_2 thin film deposited on the front side of a glass plate to provide conduction of the charge carriers, and the cathode is made of a ZnSe plate with high resistivity (10^7 Ω cm). The distance between the electrodes is micro-sized and it is easy to attain pressures of the order of 0.0133 kPa in the Ar-filled gas discharge cell.

In addition, the electrical and optical measurements of ZnSe have been carried out for the detailed understanding of its optical properties in the IR region. The gap between the electrodes changes in the range of 50–600 μm. The electrical field in the cell can be regarded as homogeneous since the maximum current was limited to 100 μA.

The discharge current varies according to the type of cathode material and plasma parameters, including pressure p, gap distance d, and the gas type. The value of the current is controlled by the high resistivity semiconductor electrode in order to avoid filamentation which causes damage to the cathode materials. The current does not exceed 10^{-4} A in the stable discharge conditions. A dc power supply was connected to the gas discharge cell and can operate up to 2500 V.

RESULTS AND DISCUSSION

The plasma current was found to increase as the gas pressure increases from 6.66 kPa to 13.33 kPa

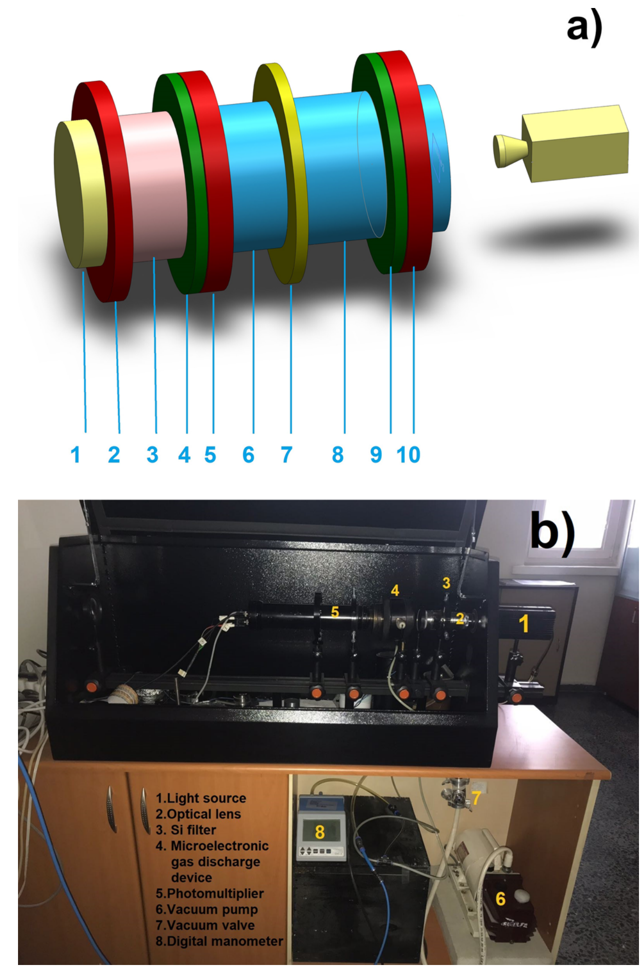

Fig. 1. (a) Infrared converter with ZnSe electrode: *1* light source, *2* Si filter, *3* *IR* light beam, *4* semitransparent Au contact, *5* ZnSe photodetector, *6* gas discharge gap, *7* mica foil, *8* UV-visible light beam, *9* transparent conductive SnO_2 contact, *10* flat glass disc. (b) The gas plasma system with a ZnSe electrode.[12,13]

when the distance between the two electrodes is fixed at 50 μm. To understand electron densities in a plasma process, electron density distributions for ZnSe have been obtained by a theoretical simulation program at two different pressures. In addition, the higher ionization rates are achieved for 13.66 kPa and the maximum electron density is around 2.8×10^{11} m^{-3}.

The density of the electrons is varied by gas pressure, and the electron distribution occupies the larger area for 6.66 kPa around the cathode, as seen in Fig. 2. The electron distribution in the plasma cell contracts at 13.33 kPa, although its value increases from 2.24×10^{9} to 2.82×10^{11} m^{-3}. The secondary electron emission for a given cathode surface strongly depends on the gas type, and its value can be neglected at high pressures.[24,25] Unfortunately, the low-pressure plasmas used in the materials processing have some limitations, such as being quite expensive. Therefore, we need gas discharges operating at atmospheric pressures.

At the same time, the theoretical calculation enables to determine the complex electron density in the plasma. Using the computational simulation to determine electron distributions in plasma requires detailed computations with a complex mesh structure.[12,13] Nevertheless, the theoretical calculations are limited and should be supported by the experimental measurements.

Figure 3 shows the FTIR spectrum of the ZnSe photodetector. The variation in the optical spectrum has been recorded in the spectral range from 2 μm to 25 μm.

It can be clearly seen that ZnSe and ZnS are sensitive to far-IR wavelengths from 10 μm to 25 μm. The absorption spectra for ZnSe and ZnS are very sensitive to the doping material. The contribution of *Se* instead of *S* directly changes the IR sensitivity, as shown in Fig. 3. FTIR spectra have been used to determine the IR response of ZnSe and a narrow spectral range has been observed.

Improvements in IR detector technology including photon detectors are associated with the development of IR-sensitive semiconductors. In these types of detectors, the photons transfer their energy to the material, or rather to the electrons as a result of the light–material interaction. The acquired electrical output signal is derived from the changed electronic energy distribution in the material.

Various microscopic techniques have been used to characterize 2D materials in order to gain a better insight into the nature of their properties.[26]

The AFM measurement has been carried out to characterize structural properties such as shape, height and size distribution for ZnSe detectors. Figure 4 shows the AFM image (5 × 5) and 3D surface morphology of the ZnSe material.

AFM has been associated with the three-dimensional topographical analysis of a sample surface with high-resolution and roughness measurements. AFM provides a useful tool for surface roughness determination, with the measurements performed on the nanometric scale. It is not easy to extract the roughness parameters from images. Commonly, the root-mean-square value is given as a value for the surface roughness. The root-mean-square average value determined by the AFM measurement is 2.041 nm. AFM is generally used for nondestructive measurements and provides real three-dimensional images with a very high spatial resolution.[27–29]

Figure 5 shows the CVC and DLE curves under the influence of various IR light beams at dark, weak L_1 and strong L_3 illumination intensities for the Townsend discharge mode.[14,15] As shown in Fig. 5, the ZnSe detector reacts to changes in IR intensity, because the absorption of IR radiation by the material is in a different proportion with regard to its initial source. The advantage of a ZnSe detector is due to its higher sensitivity compared

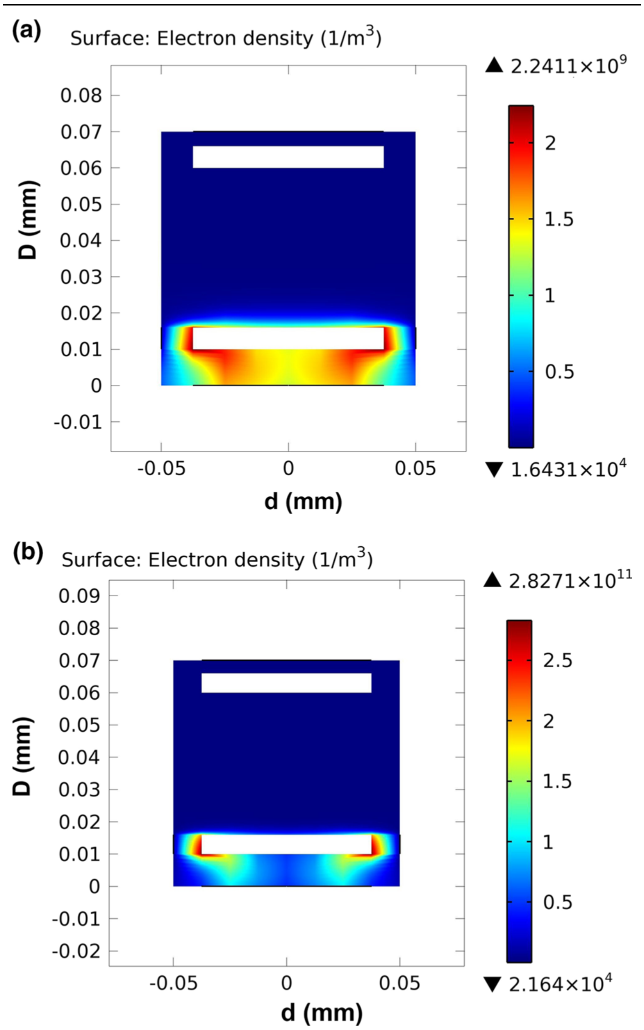

Fig. 2. Electron distributions along the discharge gap for ZnSe: (a) p = 6.66 kPa; (b) p = 13.33 kPa at 1000 V. d is the interelectrode distance between the electrodes and D is the diameter of the gas discharge cell.

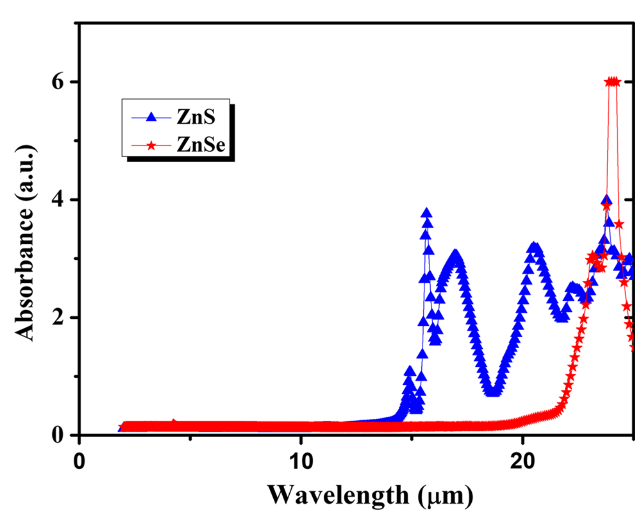

Fig. 3. Optical absorption spectra for ZnSe and ZnS.

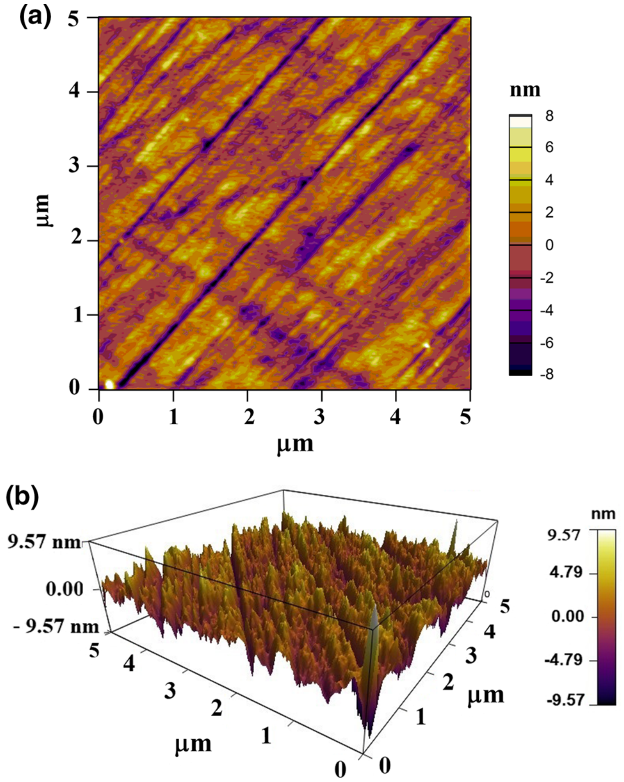

Fig. 4. (a) AFM image of ZnSe in 2D. (b) 3D surface morphology of ZnSe.

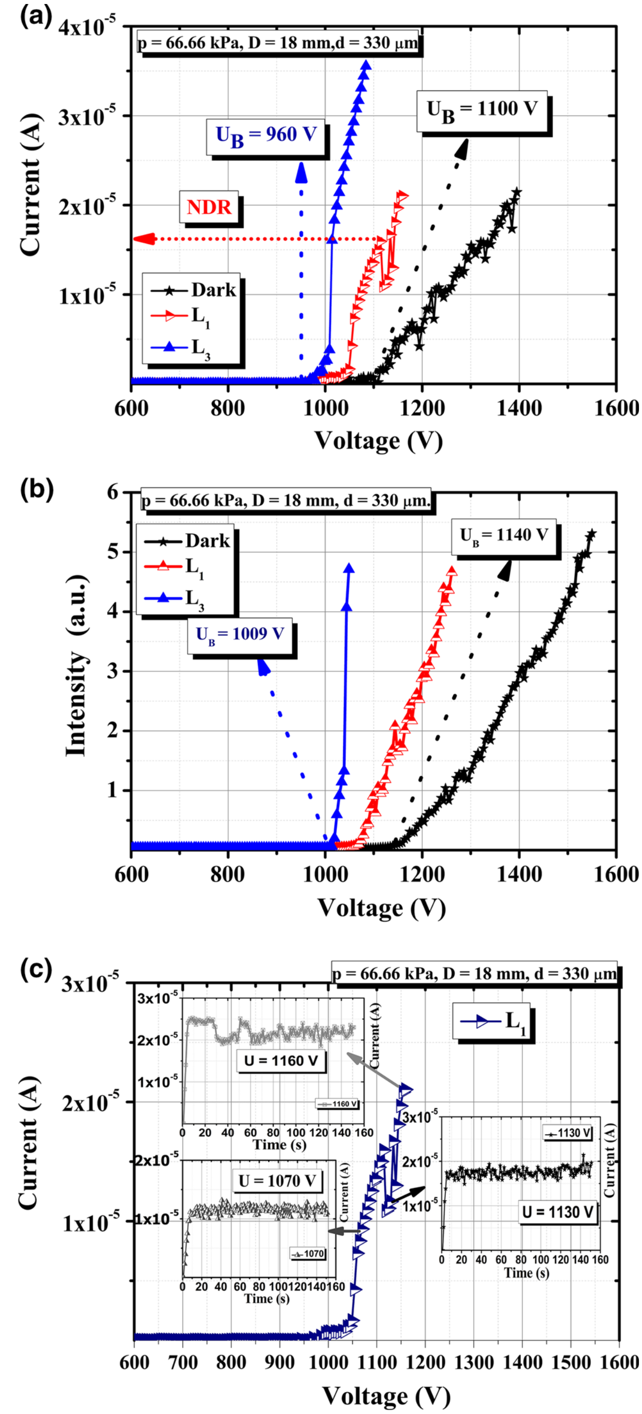

Fig. 5. (a) CVCs. (b) DLEs under dark, weak L_1 and strong L_3 IR illumination intensities for constant cathode diameter D = 18 mm, d = 330 μm at p = 66.66 kPa. (c) CVC; insets: current–time graphs for different applied voltages for L_1. U_B breakdown voltage.

to commonly used IR detectors such as GaAs.[16,17] Further, ZnSe has exhibited overwhelming advantages over GaAs material in terms of a higher IR sensitivity and better response. Moreover, GaAs is a toxic material and can damage to people's health. The IR detectors used for imaging and military applications are typically limited to their detection capability. The high IR response makes the ZnSe material suitable for use as an IR detector in technologic applications. Therefore, ZnSe can be an alternative to the other detectors in a wide spectral range according to our experimental findings.

On the other hand, the difference between the measured breakdown values, U_B, under IR illuminations are very different from each other. The values of U_B have been determined from the CVCs. The U_B value is 1100 V for L_1, whereas it is 960 V for L_3, as shown in Fig. 5a. Under high IR illumination, the gas becomes conducting at lower voltages. Moreover, the difference between the breakdown values for the DLE gave higher values compared to the CVC. That is, U_B is 1140 V for L_1 and 1009 V for L_3, as shown in Fig. 5b. We conclude that the plasma media is much more sensitive to IR illumination than the discharge current.

Technological applications of the plasma, including semiconductor processing and material treatments, and modifications of surfaces with physical and chemical processes, are of great importance for the material field.[29] IR detector technology based on semiconductors depends on the high-speed response of the IR converter at the optimum experimental parameters.

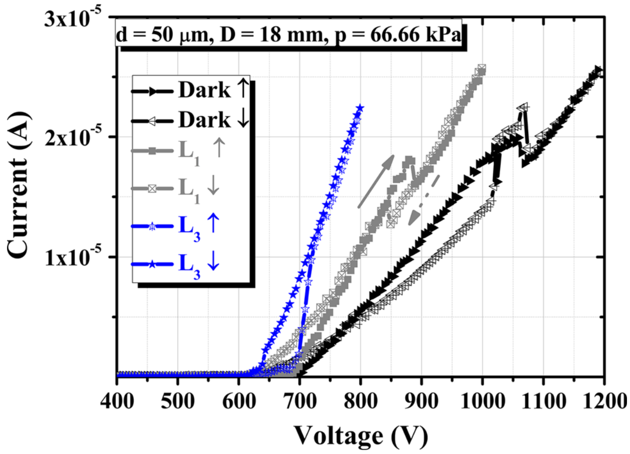

Fig. 6. Hysteresis curves in the plasma–semiconductor system in the case of dark, weak L_1 and strong L_3 illumination intensities. System parameters: d = 50 μm, D = 18 mm and p = 42.66 kPa.

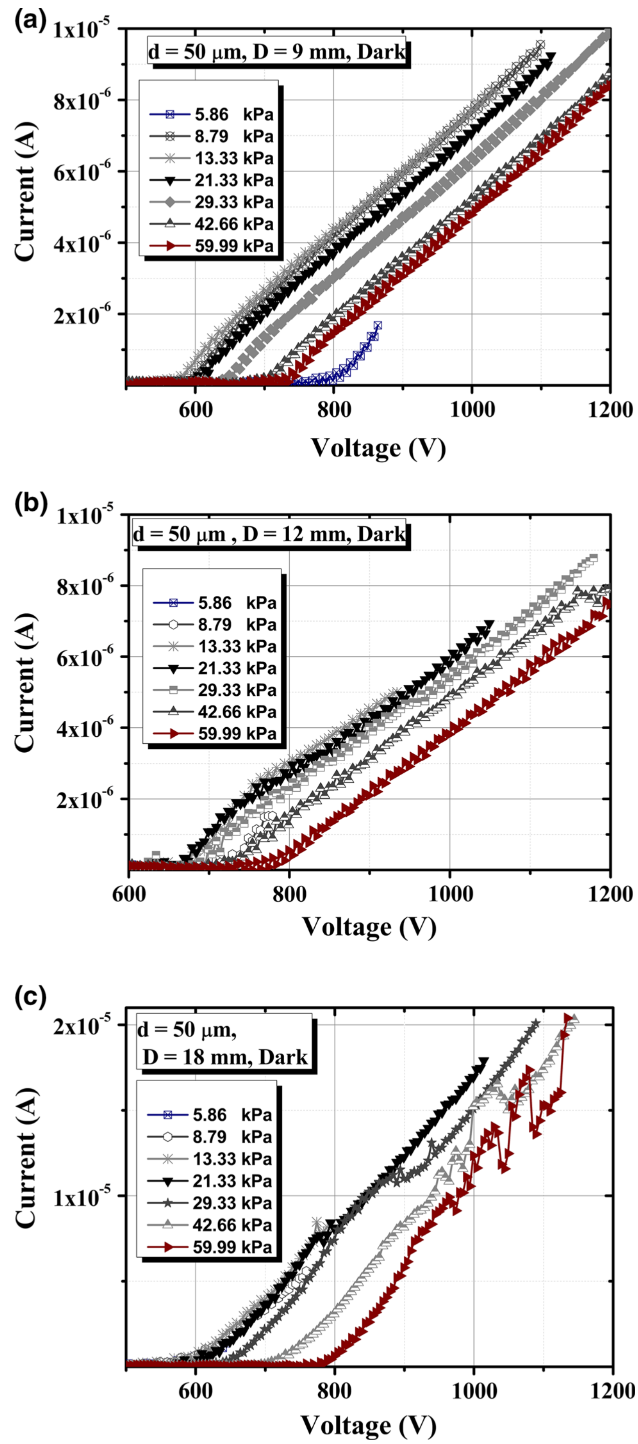

Fig. 7. CVCs as a function of gas pressure, p, at different cathode diameters: (a) for D = 9 mm, (b) for D = 12 mm, and (c) for D = 18 mm at 50 μm.

Since the electron distributions in the plasma cell are governed by both the semiconductor and the plasma, it is important to control instabilities and filament-type discharges (i.e. nonuniform discharges) in the cell. The properties of the discharge plasma depend on the operating gas between the ZnSe cathode and the SnO_2 evaporated glass disc. In addition, when the ionization rate exceeds the recombination rate in plasma depending on the gas pressure, the plasma becomes stationary. However, if the applied voltage is higher than the critical value, V_{cr}, the gas discharge makes the transition from a uniform state to a nonuniform state, leading to a potential drop and non-uniform electric field distributions.

The temporal evolution of the discharge current is illustrated in the inset of Fig. 5, which describes the unsteady situation of dc Townsend discharge. The temporal behavior of the current is explored by analyzing potential changes. The remarkable influence of voltage has been observed in the current, especially at 1160 V, which provides strong ionization. The complex behavior of the gas discharge can be controlled by a high-resistivity semiconductor plate, leading to the suppression of the instabilities in the cell. The inset in Fig. 5c also shows that fluctuations occur in the current with respect to time. The most important situation in Fig. 5 is the existence of a filamentary gas discharge mode dependent on the plasma conditions in space and time. Because of the importance of uniform plasma densities, current—time plots have been obtained for various voltages corresponding to different regions in the CVC with negative differential resistance. When the critical electric field is reached in the cell, many filaments have been observed instantaneously with arbitrary shapes.[23] Therefore, the most important event in a plasma system is to control that type of instabilities using a high-resistivity semiconductor electrode.

In Fig. 6, hysteresis curves have been provided experimentally at different IR illuminations. CVC measurements show that the hysteresis width varies due to the change in the intensity of the IR. In addition, the curves are shifting from a linear to a nonlinear character with decreasing IR intensity from L_3 to dark. This indicates that IR stimulation plays an important role in the optimization of the system. This oscillating conductivity at lower IR intensities limits the use of ZnSe material as an IR detector.

According to our experimental findings, when the value of the cathode diameter D is appropriately set, the optical properties of ZnSe can be improved and the IR sensitivity of the material can be optically increased.

Figure 7 shows the relationship between the current and the gas pressure, p, for three different cathode diameters, D, at a fixed inter-electrode distance, d. The measurements have been carried out for D = 9, 12 and 18 mm, while the gas pressure changes from 5.86 kPa to 59.99 kPa. The comparison of the currents at different cathode diameters, D, shows that the maximum current values are obtained at a higher diameter (D = 18 mm).

When the diameter of the semiconducting cathode increases, the sensitivity of the system to gas pressure is also increasing. As shown in Fig. 7c, the current is found to be several orders of magnitude higher than that at 9 mm and 12 mm. The qualities of the photodetectors are measured by their uniform spectral response to the optical signal, and their high speed and low noise in the conversion process. Samples with high resistivity have been used in order to suppress the plasma instabilities and to obtain more stable plasma media for industrial applications. In addition, the system is reliable, and the maintenance is cost-effective in optoelectronic device applications. Technological improvements on IR-sensitive materials are important in the present world, and their analysis by means of an image converter system has the ability to perform nondestructive optical tests compared to other methods. Valuable information can be obtained using an IR converter system to explore the surface properties of materials exposed to IR stimulation.

CONCLUSION

Detailed information on the IR characteristics of a ZnSe detector has been obtained in an IR image converter system. Due to the scientific and technological importance of the IR detectors, IR sensitivity has been discussed, In addition, the discharge characteristics and features are explored. Gas discharge has been performed in Ar media, experimentally and theoretically, and the electron density has been found to have varying values between 2.24×10^9 m^{-3} and 2.82×10^{11} m^{-3} for gas pressures in the plasma cell between 6.66 kPa and 13.33 kPa. The dynamics of electron distributions on a ZnSe cathode strongly depend on the pressure and interelectrode distance. This proves that a better explanation of the discharge mechanism is vital. IR radiation interacts with the ZnSe detector and the image converter can be used as a monitor by converting IR light beams to visible ones as long as the detector is exposed to IR stimulation. To the best of my knowledge, this is the first work in which ZnSe can be used for IR detection in an IR image converter. ZnSe is an alternative material for the IR detector since it can convert the IR light beam into an electrical signal with respect to various light intensities. The discharge current and light emission have been measured experimentally and the maximum current has been found to be around 3.6×10^{-5} A. The maximum DLE has been recorded around 5.6 (a.u.) via a photomultiplier. It has also been observed that the discharge current tends to transform from the uniform form to a filamentary mode at high interelectrode distances of around 330 μm. Furthermore, a hysteresis behavior has been observed at lower IR intensities for 50 μm, with even the hysteresis width changing according to the illumination intensity. The surface topolocal features of ZnSe have been explored by AFM (3D). It is observed that ZnSe material exhibits an approximately uniform surface. The breakdown voltage, U_B, is decreased from 1100 V to 960 V with increasing intensity. According to our observations, several parameters such as gas pressure, interelectrode distance and cathode diameter, should be taken into consideration to evaluate the IR performance of the ZnSe.

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