

Enhanced photoresponsivity by metal microisland in ZnO thin film based UV photodetector

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Abstract

Ultraviolet photodetectivity in ZnO thin films deposited by sol-gel technique based metal-semiconductor-metal (MSM) photodetectors is investigated. Effect of optical power level of UV radiation and bias voltages on the photoresponse behavior is studied. A two different photodetector configuration comprising, ZnO thin film embedded with microisland metals like Al and Ni were designed and tested. Photoresponsivity was found to be better for the Ni microislands embedded ZnO film as compared to those using Al microisland embedded ZnO thin films. The devices exhibited maximum photoresponsivity at $150\mu W$ above this value the devices attend to saturate. Ni/ZnO embedded Ni microislands sample exhibits highest quantum efficiency of 214% whereas Al/ZnO embedded Al microislands sample structure presents highest sensitivity of 94%. Devices based on Ni microislands embedded films exhibited gain compared to Al microislands embedded films. Enhancement in the quantum efficiency of Ni/ZnO embedded Ni microisland is attributed to the devices have higher responsivity due to the difference in work function and oxygen affinity values of Ni with the ZnO thin film layer. The study also revealed that the all devices showed a maximum photo-response at flat band voltages of MSMs.

Key Words: Photoresponsivity, microisland-metals, MSM, UV-photodetector, ZnO

تعزيز الاستجابة الضوئية بواسطة جزر معدنية مايكروية في كاشف الاشعة الفوق بنفسجية المعتمد على الاغشية الرقيقة لاوكسيد الزنك

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الخلاصة

تم التحري عن كشف للاشعة الفوق بنفسجية في الغشاء الرقيق لاوكسيد الزنك المرسب بتقنية المحلول جلاتين بتصميم وتصنيع واختبار متحسس نوع معدن-شبه موصل-معدن. ودراسة تأثير مستوى القدرة الضوئية للاشعة الفوق بنفسجية و انحياز الفولتية لتركيبين مختلفين من الكواشف الضوئية المتضمنة الاغشية

الرقيقة لاوكسيد الزنك مع الجزر المعدنية المايكروية لمعدني الالمونيوم والنيكل. وقد لوحظ ان الاستجابة الضوئية للنبائط ذات معدن النيكل كانت افضل من نظيرتها من الالمونيوم . كل النبائط كان لها اعلى استجابة ضوئية عند مستوى الطاقة 150 مايكرواط عند مستويات اعلى حدث تشبع . النيكل/اوأكسيد الزنك مع الجزر النيكلية المايكروية اظهر اعلى كفاءة كم بمقدار 214% بينما الالمونيوم/اوأكسيد الزنك مع الجزر الالمونيومية المايكروية اظهر اعلى كفاءة كم بمقدار 94%. النبلط النيكل/اوأكسيد الزنك مع الجزر النيكلية المايكروية اظهرت كسبا مقلرنة مع نبائط بينما الالمونيوم /اوأكسيد الزنك مع الجزر الالمونيومية المايكروية . التعزيز في كفاءة الكم لنبائط النيكل /اوأكسيد الزنك مع الجزر النيكلية المايكروية يعزى الى ان هذه النبائط لها استجابة ضوئية اعلى بسبب الفرق بين دوال الشغل والفة الاوكسجين مع الغشاء ال رقيق لاوكسيد الزنك . وكشفت الدراسة أيضا أن جميع النبائط اظهرت حد أقصى للاستجابة الضوئية عند فولتية الحزمة المسطحة لنبائط معدن-شبه موصل-معدن.

الكلمات المفتاحية: الاستجابة الضوئية، الجزر المايكروية المعدنية، معدن-شبه موصل-معدن، كاشف اشعة فوق بنفسجية، اوأكسيد الزنك

1. Introduction

Thin film has drawn significant interests in recent times for providing many important electronic and optoelectronic applications [1]. In particular, ZnO have attracted significant attention as thin-film wide bandgap semiconductors for UV detection, due to its unique combination of interesting electronic, magnetic, piezoelectronic and optoelectronic properties. ZnO an environment friendly material has wide direct bandgap of 3.37 eV at 300 K, a high exciton binding energy of 60 meV, excellent radiation hardness and a large photoresponse, and low cost with respect to material and growth processes [2]. There have been numerous investigations on the fabrication of ultraviolet (UV) photodetectors with ZnO thin-films having a metal-semiconductor-metal (MSM) structure [3].

To increase efficiency it is possible to increase the light trapping capability of the active layer by utilizing optical enhancement effects. This can be achieved either by means of plasmonic light scattering (by introducing scatters into the active layer) or doping to trap photo-induced charge carriers (by doping the active layer) [4-8]. Plasmonic light trapping is particularly interesting for thin film photodetectors as these films offer the potential to easily incorporate metallic nanostructures inside the active region. Beck et al. [4] have demonstrated that metal nanoparticles can suppress or enhance the photocurrent depending on the work function of the metal. The chosen metals were Ag, Al and Au. Both Al and Ag nanoparticles suppressed the

photocurrent while Au resulted in enhanced photocurrent of up to a factor of 5 near the band edge (635 nm) for nanoparticles embedded in ultra-thin PbS colloidal quantum dot films [4]. Others have reported enhanced ZnO photocurrent by using nanostructured Au and Pt metals [5]. They have attributed this enhancement to the creation of many interface states which act as traps of minority carriers. These traps can increase the lifetime of minority carriers and in turn increase the photocurrent of the devices. Further enhancement may be partly due to scattering and the surface plasmon effect, which can provide the increase in optical absorption and responsivity [5]. Lai et al., [6] have studied the surface-plasmon emission from ZnO by using Ag and Au coatings. The enhancement in emission intensity is attributed to the interaction between the spontaneous recombination in ZnO and surface plasmons arising from metal interfaces.

In the present study we report on the fabrication and characterization of Al or Ni/ZnO interdigitated MSM UV photodetectors having three different arrangements. Specifically, devices having Al or Ni microparticle embedded ZnO films were compared. The electrical characteristics and optical response of the devices were studied and compared to explore the potential application of these configurations as UV photodetectors. All measurements were recorded at room temperature (300 K).

2. Experiment

The deposition of the ZnO thin film active layers was carried out by using the sol-gel technique. The substrates used for deposition were *p*-type Si <100> (~380 μm thick) with a resistivity of 2-7 Ωcm. Before deposition of the ZnO films, the substrates were cleaned, the cleaning process was described in detail in our previous work [9]. Zinc acetate dihydrate is well known as a starting material for the preparation of ZnO sols for coatings. The ZnO thin films were synthesized based on a procedure described elsewhere.

For Al or Ni microparticles embedded in un-doped ZnO, microparticle arrays were fabricated with the help of a shadow mask technique. A standard sieve mesh with aperture width of 80 μm was used as a mask during the thermal evaporation of Al or Ni powder (99.99%) on cleaned Si substrates. This resulted in a uniform array of Al or Ni microparticles having diameters 80 μm. ZnO films were prepared by spin

coating the sol-gel on the wafers for 40 seconds at a speed of 4,000 rpm. This step was followed by preheating the coating at 100°C for 5 min and post-heating at 450°C for 1 h in an N₂ ambient tube furnace. Arrays of four planer type MSM diodes were created on all samples (2" diameter Si substrates). MSM sensors were fabricated on the top surface of the ZnO films with an interdigitated finger electrode. Ni was deposited via thermal evaporation using a shadow mask fabricated by a wire cut machine (model W-A430, ACRA, USA). The deposited fingers were designed to be $w=150\ \mu\text{m}$ wide and 4000 μm long with $s=150\ \mu\text{m}$ wide spacing. Immediately prior to the fabrication of metal electrodes, the wafer was dipped in an organic solution and deionized water.

For the investigation of the carrier concentration and mobility, Hall effect measurements were performed using an Ecopia HMS 3000. The absorbance spectra of ZnO thin films were studied via double beam spectrophotometry using a Perkin Elmer, Germany model-Lambda 25 in the wavelength range from 200-1,000 nm. The thicknesses of the Al or Ni microparticle embedded ZnO films were estimated to be in the range of 300 nm, respectively as measured by TFProbe, from Angstrom Advance Inc.

The current-voltage (I-V) characteristics were measured using a semiconductor characterization system (SCS-4200, Keithley) at room temperature (300 K) for applied voltage ranging between -5 to +5 V. The fabricated MSM UV photodetectors were studying under dark as well as under exposure to UV light at optical power of 50, 100, 150, and 200 μW at room temperature (300 K).

3. Results and Discussions

Figure 1 shows the microscope image of the microisland metal coated by ZnO thin film. The electronic parameters were measured by van der Pauw and Hall methods Surface resistivity ρ is found to be 32.9 $\Omega\cdot\text{cm}$, Hall mobility μ was 21.4 $\text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$, and carrier concentration was $9.23\times 10^{15}\ \text{cm}^{-3}$.

The bandgap of ZnO is evaluated from the absorbance spectra of ZnO obtained by using double beam spectrophotometry in the wavelength range from 200-900 nm. Figure 2 shows the absorption spectra the inset shows the Tauc plot

adsorption spectra for ZnO films At room temperature (300 K) the values of optical bandgap is estimated to be 3.4 eV.

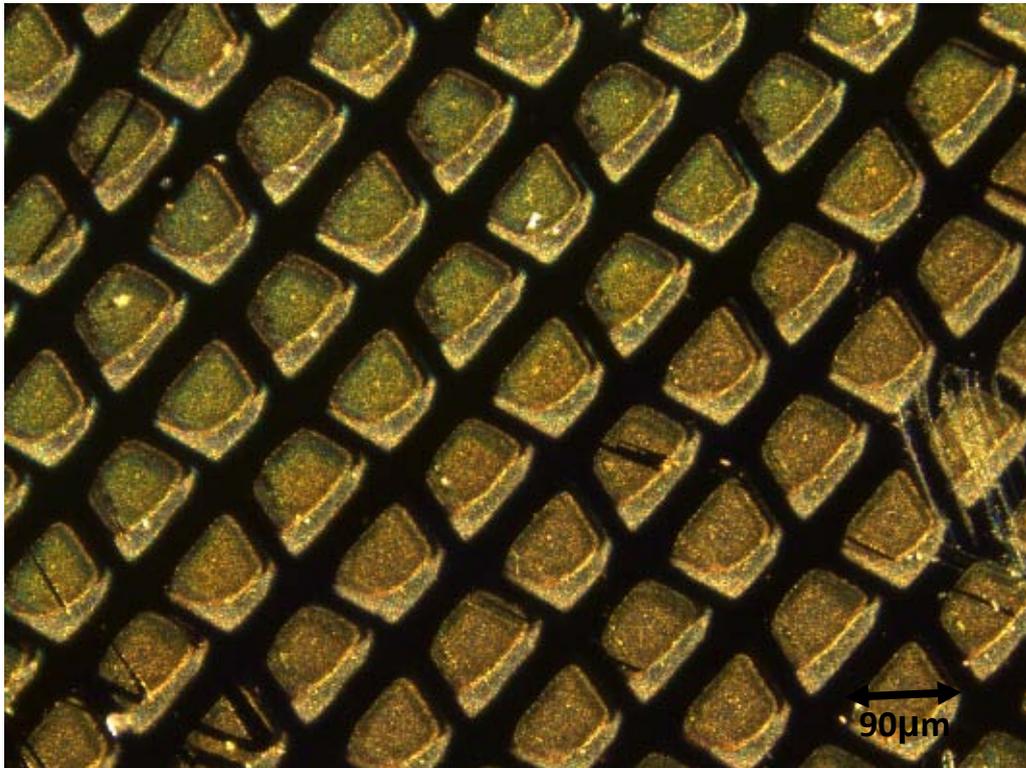


Figure 1: The microscope image of the microisland metal coated by ZnO thin film.

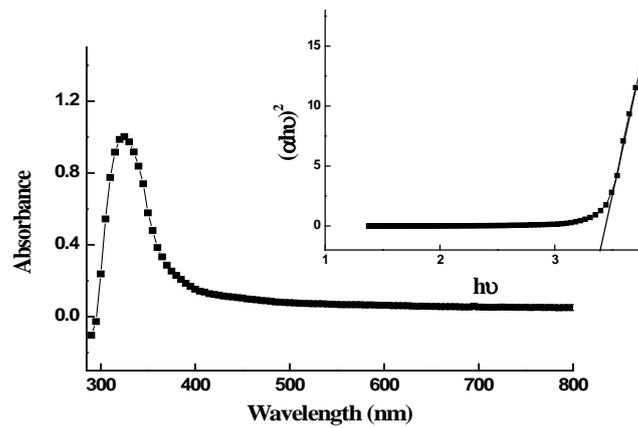


Figure 2: The absorbance versus wavelength. The inset in the figure is $(\alpha h\nu)^2$ versus $h\nu$ plot for estimation of band gap.

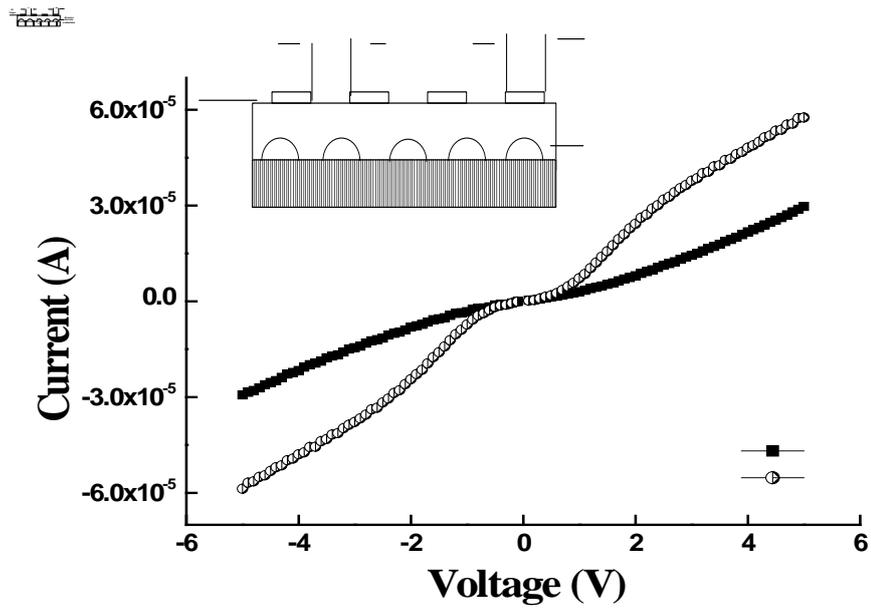
Figure 3 shows the I-V characteristics measured in the dark and under UV illumination (365nm) at 200 μ W optical power, the complete devices schematically detailed in the insets figure. The devices show typical behavior for interdigitated MSM diodes. Figure 3(a) shows the I-V characteristics of Al/ ZnO embedded Al microparticles, the illumination current increased by a factor of 2 at 5 V as compared to dark condition. Meanwhile the illumination current for devices based on Ni/Ni microparticle embedded films increased by a factor of 1.8 at 5 V as shown in Fig. 3(b). A MSM PD is a unipolar device with two back-to-back junctions formed on the same semiconductor surface. Figure 3 shows the current transport mechanism doesn't follow pure field emission, it is clearly that the dominant mechanism is a thermionic-field emission.

The values of barrier height, ideality factor and saturation current were extracted from the I–V characteristics for the two devices. Analysis of the results show that the saturation currents of 5.28×10^{-7} A and 5.74×10^{-6} A for the devices based on Al and Ni microparticles enhanced films, respectively. The values of barrier height (ϕ_B) evaluated at room temperature (300 K) were found to be 0.627 and 0.565 eV, respectively.

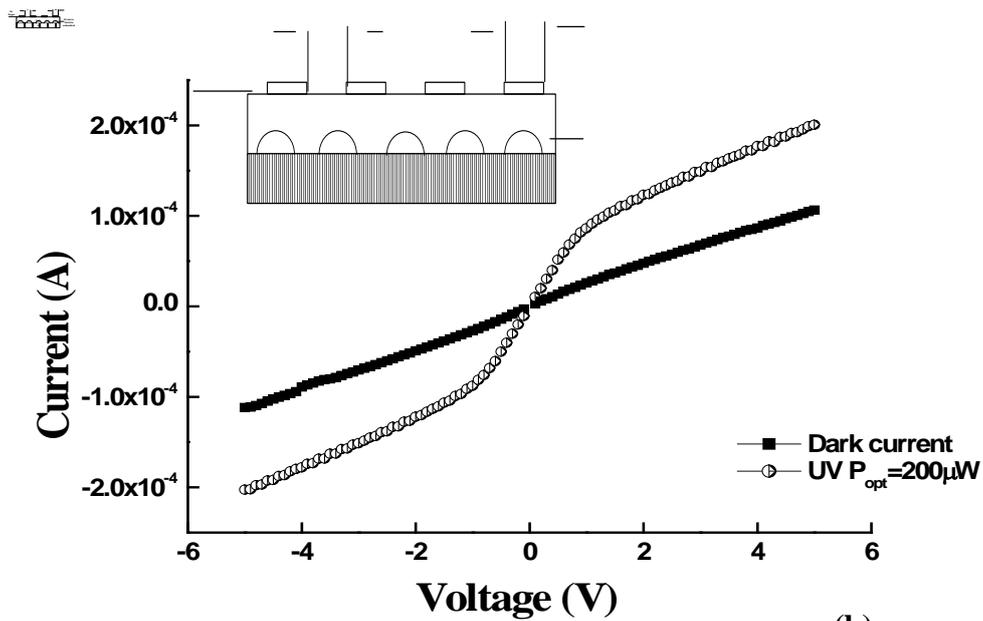
For the two photodetector geometries studied, Fig. 4 shows the photocurrent as a function of different levels of optical power (50-200 μ W) of UV illumination 365 nm wavelength at 5V applied voltage measured in the air under at room temperature (300 K). The photocurrent is defined as the difference between the current under illumination and the dark current [10]. The shape of the curves indicates that the devices exhibited saturations at higher optical power (150-200 μ W) of UV illumination, while for a lower power the optical current increased linearly. The figure also reveals that the Ni microparticles embedded films derived devices have higher photocurrent for same optical power levels. The studied devices exhibit same level of UV detection capability under bidirectional voltage operation. As the UV optical power is increased, a significant increase in forward- and reverse-bias current is observed. All devices show increasing in the photocurrent up to an illumination level of 150 μ W of optical power, after which the devices become saturated. The mechanism of UV light detection for ZnO films is attributed to the desorption and adsorption of oxygen at the ZnO surface [11]. Under dark conditions oxygen is

adsorbed by capturing a free electron from the surface of *n*-type ZnO, creating a depletion layer near the surface. This depletion layer results in a decrease in film conductivity. Under UV illumination, photogenerated electron–hole pairs drift in the direction of the applied electric field extending into the depletion layer. Holes move towards the surface and neutralize the adsorbed oxygen which causes the surface conductivity to increase [11].

The contrast ratio (sensitivity) is an important figure of merit for an UV detector. Figures 5(a) and (b) show the variation of contrast ratio with positive applied voltage for the studied detectors on exposure to UV illumination (50-200 μ W). As the optical power increases, the sensitivity increases in both directions of applied bias. When the bias reaches near flat band voltages V_{FB} region the sensitivity decreases until saturation. The stable range of the sensitivity occurs after the photodetectors reach at flat band bias conditions. Comparison of Figures 5(a) and (b) shows that at higher level of applied voltages (4-5 V) there is no significant difference in the contrast ratio of devices based on Al and Ni microparticle embedded films, however,



(a)



(b)

Figure 3: I-V response for (a) Al/micro Al particles embedded ZnO photodetectors (b) Ni/micro Ni particles embedded ZnO photodetectors. The inset figures show the schematic diagram of the MSM photodetector geometries.

the last one tend to saturate faster than Al ones. This makes, devices based on Ni microparticle embedded films propose to operate at lower bias. The enhancement in the detection capability may be attribute to an increase in light absorption due to plasmonic light trapping. Beck et al. [4] previously reported that improvements in the photoresponse can be achieved by exploiting the strong interaction between propagating light fields and metal nanostructures, which scatter incident light and couple it efficiently into absorber layers.

Figure 6 shows the responsivity as a function of the applied voltage at different level of optical power (50-200 μW) for the studied devices. The responsivity R can be defined as the photocurrent divided by corresponding optical power [10]. As the optical power of UV light increases, the responsivity increases until reaching a its maximum value at 150 μW (see Fig. 6). At increasing power beyond 150 μW the responsivity degrades, which is due to the saturation of photocurrent as seen in Figs. 3. Also it is clearly seen that the increasing rate of the resposivity is much higher at the point before reaching flat band voltage than this specific voltage. The responsivity after reaching flat band voltage attends to saturate.

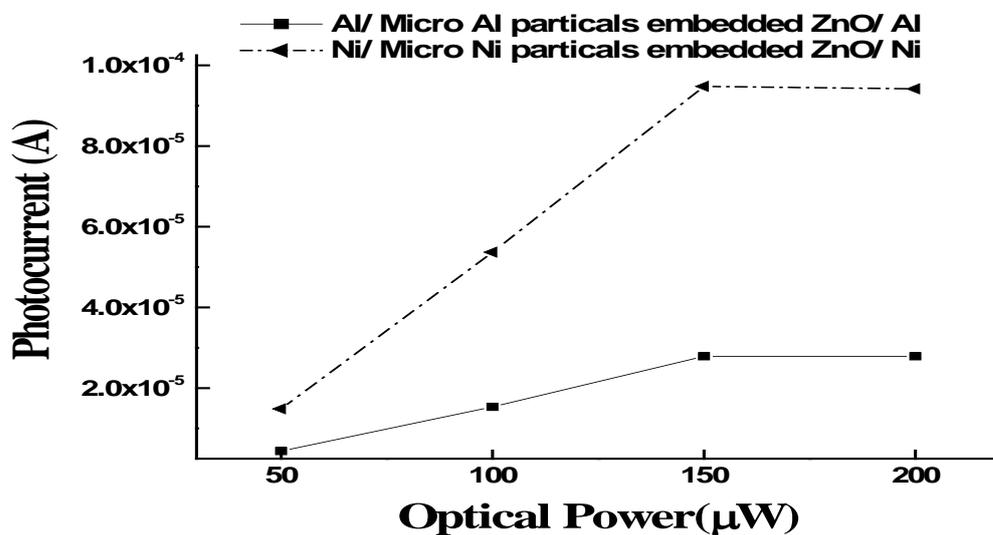


Figure 4: Photocurrent versus optical power of UV light.

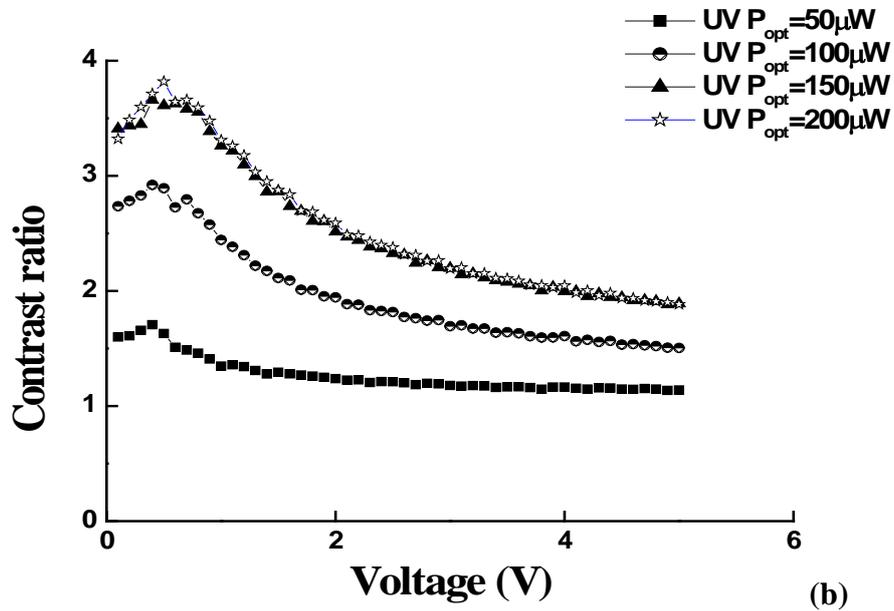
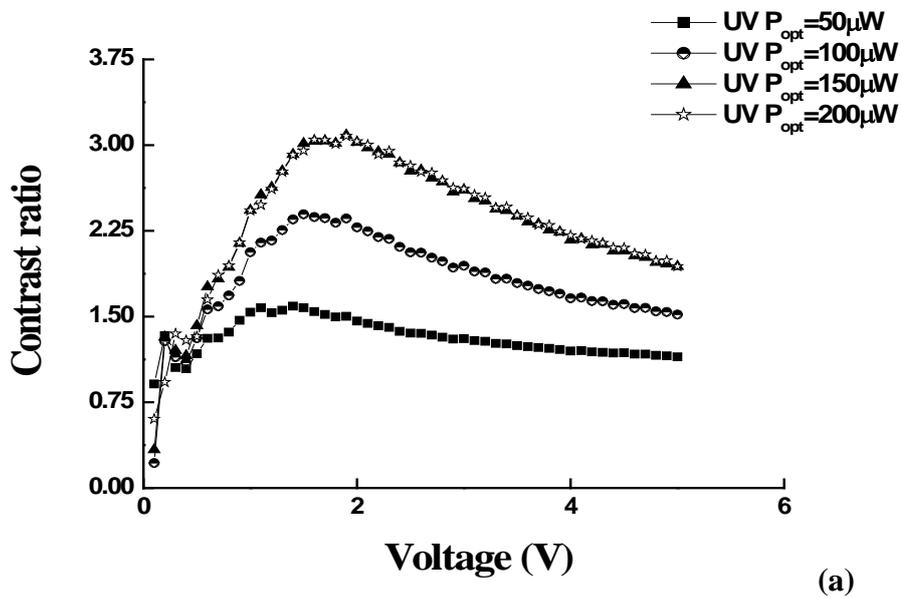


Figure 5: Variation of contrast ratio of the photodetectors versus voltage
 (a) Al/micro Al particles embedded ZnO photodetectors (b) Ni/micro Ni particles embedded ZnO photodetectors.

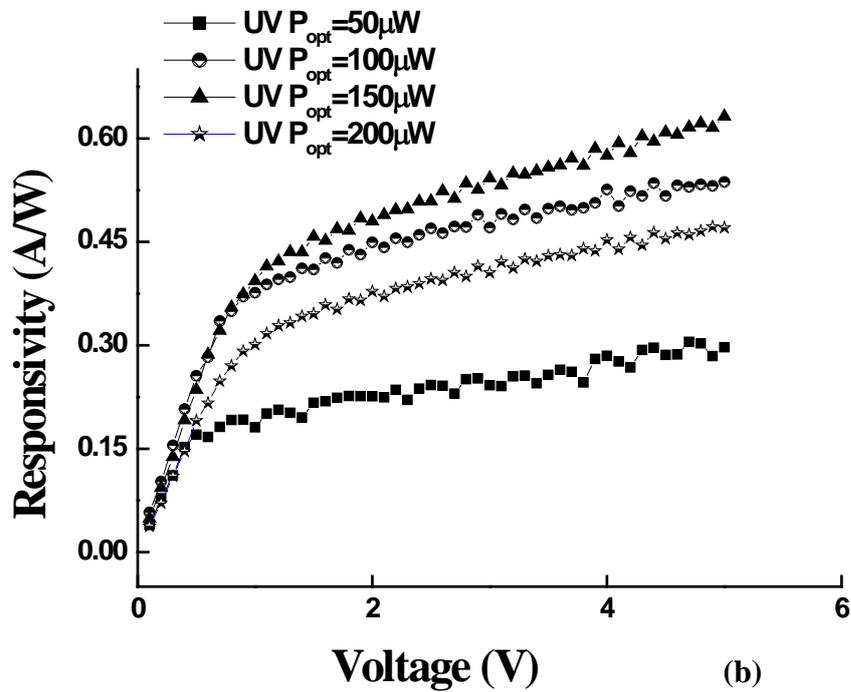
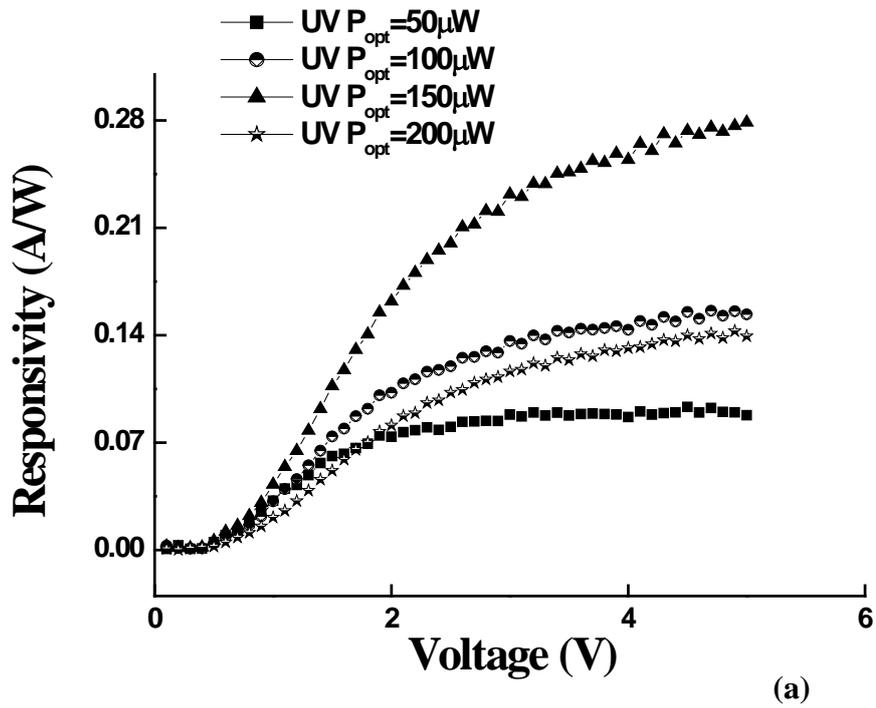


Figure 6: Variation of responsivity of the photodetectors with optical power of UV light (a) Al/micro Al particles embedded ZnO photodetectors (b) Ni/micro Ni particles embedded ZnO photodetectors.

Figure 7 shows the quantum efficiency η as a function of the optical power for the studied devices operating at 5 V. The quantum efficiencies increased with increasing optical power up to a maximum value at 150 μW , after which the efficiencies start to degrade due to saturation of the photocurrent. The maximum efficiencies of the devices studied were 94% and 214% for devices based on un-Al and Ni microparticle embedded films, respectively. The maximum efficiency for Ni microparticle embedded devices is larger than Al one, this indicates that the device exhibited gain may be attributed to the devices having higher responsivity due to the difference in work function and oxygen affinity values of Ni with the ZnO thin film layer. This study reveals that embedding Ni microparticles in ZnO films can result in enhanced photodetector performance and efficiency, specifically when operated at the stable region above the flat band conditions.

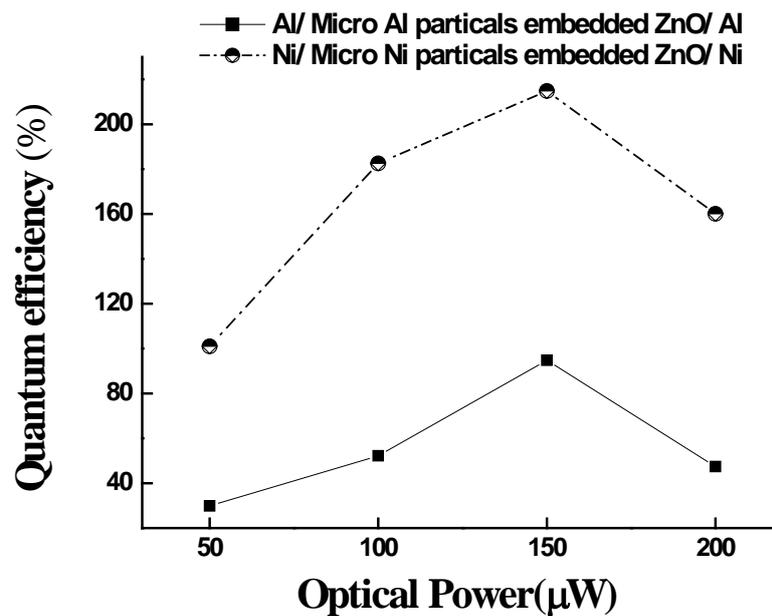


Figure 7: Efficiency as a function of optical power of UV light.

4. Conclusions

We have reported on the characterization of ZnO-based interdigitated metal–semiconductor–metal (MSM) Schottky barrier UV photodetectors using Al or Ni microparticle embedded ZnO films were compared. The ZnO thin films were prepared by the sol–gel technique. The I-V characteristics of the MSM were examined by taking into account the effect of different optical power and operate bias voltages. We have shown that under certain conditions the devices exhibited maximum performance. Devices based on Ni microparticle embedded films exhibited gain compared to Al microparticle embedded films. The photoresponse properties under UV illumination were studied at room temperature, where it was found that the performance of the photodetector can be improved with respect to photocurrent, contrast ratio, dark current, and efficiency by incorporating Ni metal microparticles in ultra-thin un-doped ZnO films. Furthermore, the studied photodetectors operate most effectively and steadily at the voltages above a flat band bias condition. Devices based on the embedding of a micro-metal array are expected to find applications in plasmonic and photonic devices.

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