

# Highly UV sensitive Sn nanoparticles blended with polyaniline onto micro-interdigitated electrode array for UV-C detection applications

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#### Abstract

Highly UV sensitive sub-5 nm Sn nanoparticles-Polyaniline (Sn (NPs)-PANI) composite material has been formulated by chemical polymerisation. A thin film of the composite is deposited on Micro-Interdigitated Electrode ( $\mu$ -IDEs) array for photodetector application. Considerably, higher optical density (10–12), w.r.t carbon of Sn (NPs) in Sn (NPs)-PANI/Al-IDE/ Glass structures exhibit the exceedingly enhanced sensitivity towards UV illumination. There is substantial large contrast ratio of ~ 2290 at – 1 V, significantly large responsivity ~ 3.05 A/W, detectivity of ~ 2.26E + 13 Jones and reasonable rise/fall time of ~ 0.7/1.7 s observed for Sn (NPs)-PANI/Al-IDE/Glass devices. Surface morphology, phase analysis, and elemental composition of Sn–PANI systems have been investigated by X-ray diffraction and Energy Dispersive X-ray analysis (EDX), respectively. Transmission electron microscopy (TEM) analysis confirms the size of the Sn (NPs) and blend with Polyaniline. The significantly enhanced sensitivity of ~ 228514.3 for  $\lambda$  ~ 254 nm establishes the clear potential of the fabricated structure for UV-C detector application.

# 1 Introduction

Ultraviolet (UV) photodetectors have drawn immense attention due to their applications in various fields like industry, military, radiation detection, flame detection, optical, chemical, medicine, non-line-of-sight communication, environment and biological fields [1–6]. Generally, UV light is classified into four spectral regions based on the wavelength ( $\lambda$ ): (i) UV-A ( $\lambda$  – 400 to 320 nm), (ii) UV-B ( $\lambda$  – 320 to 280 nm), (iii) UV-C ( $\lambda$  – 280 to 200 nm) and (iv) far UV ( $\lambda$ – 200 to 10 nm). Among these, the Solar blind UV-C photodetectors have attracted considerable attention owing to their applications in missile plume sensing, flame detection, UV astronomy, ozone layer monitoring, chemical-biological

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<sup>2</sup> Department of Electronics and Communication Engineering, National Institute of Technology Silchar, Silchar, Assam 788010, India agent sensing, water purification, medical, submarine and space applications [7–9].

The commercially available Si-based UV photodetectors have limitations; small Si band gap of 1.1 eV, low responsivity and higher cost due to the ultrahigh vacuum, high temperature, expensive substrates, rigorous fabrication processing and also involvement of expensive optical filters to terminate photons with low energy [10]. In the past decade, UV-C photodetectors of Diamond, ZnMgO, AlGaN, and  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> material systems are explored and used [11–14]. Alternatively, the use of polymer films in composition with the nanoparticles or colloidal quantum dots as photoconductors are a crucial step for realization of low cost photodetectors, ranging from UV to the infrared wavelength [15, 16].

Recently, research progress of composite and nanostructures such as ZnO nanowires [17], PANI-TiO<sub>2</sub> composite [18], single layer graphene-TiO<sub>2</sub> composite [19], PANI-Au nanoparticles (NPs) [20], etc. have eliminated the use of any extra accessories like filters and ushered a new fabrication technique for the low cost and flexible photodetectors. Among the above, PANI based composites have drawn significant attention due to their enhanced photodetecction properties that are unattainable either in a pure or in a doped form [20–22]. PANI based composites have been extensively studied for the detection of dopamine [23], microbial fuel cells [24], photo-detection [20], chemical sensors and biosensors [25]. Note that, few efforts have been reported in the literature [20] related to the photo-detection property of the polyaniline-metal nanoparticles composite.

Metallic nanostructures can strongly absorb and scatter light due to their ability to support surface plasmon (SP) resonances. These are coherent oscillations of surface conduction electrons that can often be excited by light in various ways and manifest themselves as evanescent (confined) surface waves from a classical electrodynamics perspective. Hence, they are the most desirable candidate for the Photodetection application. There are several reports supporting the SPs of nobel metals (Ag and Au) in the visible spectral region [20, 26] and near UV [27, 28], whereas a very scare reports of the metallic nanostructures active in the UV-C region. J. M. McMahon et al. reported that Sn nanoparticles(<20 nm) exhibits SPs in the deep UV [29]. The various applications of Sn nanoparticles include anode for lithium-ion batteries [30], gas sensing [31], hydrogenation of Polyenes [32] and as dopant with inorganic material for photocatalytic activity [33] are demonstrated. There is no such reports available of Sn nanoparticles blend with polyaniline for UV detection.

The preparation of metallic nanostructures can be classified into physical and chemical methods. The physical method includes vapour condensation methods [34], spray pyrolysis [35], sonochemical synthesis [36, 37], sol-gel synthesis [38], thermochemical decomposition of metal-organic precursors in flame reactor [39] and other aerosol processes which have been named after the energy sources applied to provide the high temperature during gas-particle conversion [40], whereas the chemical method [41, 42] are based on the reduction of metal ions or decomposition of precursors to form atoms, followed by aggregation of the atoms. Nanoparticles prepared by chemical methods generally have a narrow size distribution. The chemical route also involves the water-in-oil (W/O) micro emulsion technique. In this technique, the surfactant is used to cap the metal ions and further reduction of the ions using reducing agent and separation of the nanoparticle in the oil phase.

There are several ways to prepare the composites of conducting polymer and metal nanoparticles. It includes (i) one pot approach, (ii) reducing the metal salt with the conducting polymer, (iii) synthesis of conducting polymer by electrochemical oxidative polymerization followed by the electrochemical reduction of metal salt, and (iv) preparation of the NPs followed by either chemical/electrochemical polymerization of the monomer around the NPs or dispersion of the NPs into a polymer matrix [43, 44]. In literature, various process techniques have been reported on the synthesis of Sn (NPs) nanoparticles using facile hydrothermal process [45], modified polyol process [46, 47] and wet reduction method [48], etc.

The u-electrode array including electrode shape, material quality and spacing between the fingers can greatly influence the device performance [49, 50]. The periodic array of µ-IDE's parallel in-plane fingers play an important role to build up the highly sensitive photo detector. Recently, µ-IDEs are commonly used in humidity sensors [51], chemical sensors [52] and Biosensors [53] applications. The implementation of  $\mu$ -IDEs in photodetectors has led to a huge attention in the bandwidth in comparison to a conventional one, due to the higher active area [54, 55], while for the polymer-on-metal( $\mu$ -IDE) structure, the electrical behaviour is much better than metal-on -polymer, due to the reduced density of the defects [56]. It has been observed that increasing the number and size of the µ-IDE's fingers (up to a certain limit), drastically improves the signal strength without hampering the sensitivity [53, 57, 58]. The  $\mu$ -IDE's structure have been investigated with PANI-Au nanoparticles [20], ZnO nanofibres [50], SrTiO<sub>3</sub> [49], single crystal GaN [59] and Poly(3-hexylthiophenen-2,5-diyl) [57] for photodetection applications. To the best of the authors' knowledge, limited literature is available on the formation of sub-5 nm Sn (NPs) nanoparticles using water-in-oil emulsion technique.

In this work, we synthesized for the first time the Sn(NPs)-PANI composite using water-in-oil emulsion technique, followed by the polymerisation of aniline in the presence of the Sn (NPs), to cap the nanoparticle in the polymer fibre chain. Next, the composite has been studied for its UV detection property by depositing thin film of composite on the Al based  $\mu$ -IDE array. Since the organic compounds have higher resistance, the use of  $\mu$ -IDE array effectively reduces the resistance hence, increases the effective sensitivity of the device [52].

#### 2 Experimental

#### 2.1 Materials and instruments

Fisher Scientific made monomer aniline (purity 99%), Oxidant Ammonium peroxydisulphate (APS) (purity 98%), and hydrochloric acid (HCl) is utilized to polymerize the aniline. Merck made m-cresol (purity 99.5%) was the solvent. For the preparation of the Sn(NPs) using water-inoil (W/O) micro emulsion technique, the metal salt SnCl<sub>2</sub> was obtained from fisher scientific, the surfactant Dioctyl sulfosuccinate sodium salt (AOT), the oil hexane and the reducing agent Hydrazine hydrate were purchased from Sigma Aldrich. Note that, all the chemicals were utilized as received without any further purification.

#### 2.2 Characterization

The electrical characteristics are determined using Keithley 4200 SCS in dark and under 254 nm UV illumination from UV lamp (power 300  $\mu$ W/cm<sup>2</sup>). The as prepared Sn (NPs) were confirmed using Transmission electron microscopy (TEM) and Electron X-rays diffraction (EDX). The chemical phases are investigated by the X-ray diffraction (XRD) of Agilent Supernova diffractometer with Cu K<sub>a</sub> source ( $\lambda$  = 1.5418 Å) at an accelerating current and voltage of 0.80 mA and 50 kV, respectively.

# 2.3 Synthesis Sn nanoparticles

The Sn nanoparticles were prepared using 0.04 M of SnCl<sub>2</sub> salt, 0.05 M of the AOT as the surfactant and 0.16 M of Hydrazine Hydrate as the reducing agent. Initially, 100  $\mu$ l of the surfactant was added dropwise to 2 ml of Sn salt (0.04 M) and stirred for 5 min at 600 rpm. Further, 8 ml Hexane was added and the solution was stirred for 10 min at 600 rpm. After stirring 0.2 ml reducing agent was added dropwise to the above solution to reduce the Sn<sup>2+</sup> ions into Sn (NPs) as shown in Fig. 1. Finally, the above solution was stirred for 8 h at 600 rpm to obtain the desired size and quantity of the nanoparticles.

# 2.4 Synthesis of Sn (NPs)-PANI composite

The composite was prepared by adding the nanoparticle during chemical polymerization of the monomer lead to the capping of the NPs into a polymer matrix. Sn(NPs)-PANI composite is synthesized chemically by the oxidation process at ~0–5 °C. Initially, 0.2 M aniline monomer is dissolved in 100 ml of HCl (1 M), and the solution cooled at 0 °C. Then, 0.5 ml of the nanoparticle solution in hexane was added and stirred for next 15 min. After that, 33 ml of 0.8 M solution of ammonium peroxydisulphate  $((NH_4)_2S_2O_8)$  in HCl (1 M) solution was added dropwise to the monomer aniline solution; continuous stirring changes the color to green which physically signifies polymerization. The stirring was continued for next 4 h at ~0 °C to achieve the desired molecular weight of the polymer as shown in Fig. 2. Next, the solution was kept overnight at ~0 °C to allow settling down of the resultant polymerized Sn(NPs)-PANI precipitates, followed by acetone and then DI water rinse to remove the aniline oligomers. Further, the precipitates were vacuum dried at 60 °C for 12 h to obtain emeraldine Sn(NPs)-PANI powder. Ensuing to this, Sn(NPs)-PANI is mixed with m-cresol in the ratio 1:10. Finally, the solution is stirred at 60 °C for 2 h followed by ultrasonic treatment for 15 min to obtain a homogeneous Sn(NPs)-PANI composite solution.

#### 2.5 Fabrication of the Al µ-IDE array

Glass slide purchased from bluestar is cleaned with: sonication in (i) soapy solution for 10 min, (ii) DI water for 10 min, (iii) acetone boiling for 10 min @ 60 °C, (iv) Sonication in IPA for 10 min, (v) N<sub>2</sub> gas dry, and (vi) dehydration bake at 200 °C for 15 min. The samples were allowed to cool down till room temperature (RT). Al thin film (~100 nm) was deposited over the glass samples using thermal evaporator under ultra-high vacuum of ~ $1.0 \times 10^{-6}$  mbar as shown in Fig. 3b. After that the SU-8 (2002, Micro-Chem) photoresist was spin coated on the Al/glass samples using the two step method: (i) The samples were spin coated at 500 rpm for 10 s for uniformly spreading the photo resist over the substrate and (ii) immediately to



Fig. 1 Synthesis Process of Sn(NPs) using water-in-oil micro emulsion technique



Fig. 2 Synthesis process of the Sn(NPs)-polyaniline composite



Fig. 3 Fabrication process of Sn(NPs)-PANI/Al-IDE µ-IDE structure of photodetector

3000 rpm for 30 s to deposit uniform photo resist film, at an acceleration of 100 and 300 rpm/sec, respectively (Fig. 3c). The samples were then subjected to pre-exposure bake (PB) at 97 °C for 10 min and then cooled down to RT. Ensuing this, the samples were exposed using Maskless Optical Lithography (Intelligent Micro Patterning) to pattern  $\mu$ -IDE structure as shown in Fig. 3d followed by post-exposure bake at 112 °C for 15 min. Thereafter, samples were developed using SU-8 developer (Micro-Chem) for 1 min followed by IPA rinse, N<sub>2</sub> dry and hard bake at 150 °C for 20 min. In order to define the Al  $\mu$ -IDE patterns, samples were etched using Al etchant (DI water, Acetic Acid, Nitric Acid, Ortho phosphoric acid,

in the ratio 1:2:2:10) for 2–4 min at 50 °C with constant stirring of 200 rpm and were washed with DI water couple of times. Further, the undesirable SU-8 was removed by dipping the samples in N-Methyl-2-pyrrolidone (NMP), at 60 °C for 12 h under constant stirring of 100 rpm, and rinsed by IPA, DI water back to back as shown in Fig. 3e. Here, the dimensional parameters of the  $\mu$ -IDE array for the present study are: width (W) = spacing (D) = 300  $\mu$ m, length (L) = 0.2 cm and number of  $\mu$  electrode fingers (N) = 17. Finally, the Sn(NPs)-PANI composite was spin coated over the Al  $\mu$ -IDE electrode as shown in Fig. 3(f).



Fig.4 Current density–Voltage (J-V) Characteristics of Sn(NPs)-PANI/Al-IDE/Glass, structure. The graph shows the semi-log plot of dark and photo (254 nm illumination) J-V characteristics of Sn(NPs)-PANI/Al-IDE/Glass,  $\mu$ -IDE structure

#### 3 Results and discussion

The current density-voltage (J-V) characteristics of Sn(NPs)-PANI/Al-IDE/Glass structure, obtained by sweeping the voltage from -1 to +1 V are illustrated in Fig. 4. The Sn(NPs)-PANI/Al-IDE/Glass structure shows a small rectifying behaviour with a rectification ratio (i.e. the ratio of forward ( $I_f$ ) to the reverse ( $I_r$ ) current) of ~5.83 at a bias voltage of 11 VI, probably due to the encapsulation of Sn (NPs) in Polyaniline [60, 61]. From Fig. 4, it is clear that there is a significant variation in both the forward and reverse current on UV illumination, ascribed to the generation of electron-hole pairs by the process of photo-generation. Thus, the Sn(NPs)-PANI/Al-IDE/Glass depicts photodetector properties, with the contrast ratio (i.e. the ratio of the photo current (I<sub>bh</sub>) to the dark current (I<sub>d</sub>)) of ~2290 at -1 V. Therefore, the significantly higher contrast ratio ~2290 of the Sn(NPs)-PANI/Al-IDE/Glass device system supports its potential candidature as an efficient UV-C photodetector.

The responsivity ( $R_{UV}$ ), and the photoconductive gain (g) of Sn(NPs)-PANI/Al-IDE/Glass,  $\mu$ -IDE structure is computed from the following relation [4]:

$$R_{UV} = \frac{I_{PH}}{P_{OPT}} \tag{1}$$

$$g = \frac{1240 \times R_{UV}}{\lambda(nm) \times \eta} \tag{2}$$

where  $I_{PH}$ ,  $P_{OPT}$ ,  $\lambda$  (nm), and EQE, are the photocurrent at -1 V, the optical power, the wavelength (nm) of the incident UV light, and the external quantum efficiency (EQE assumed 1 for calculations [55]), respectively. Using Eqs. (1)

and (2), the responsivity ( $R_{UV}$ ) and photoconductive gain (g) of Sn(NPs)-PANI/A1-IDE/Glass,  $\mu$ -IDE structure are calculated as ~3.02 A/W and 12.6, respectively, which are much higher than photodetector reported in literature [17, 62, 63]. The sensitivity and the specific detectivity are calculated as ~228514.3 and ~2.26E + 13 Jones respectively from the following relation:

$$S = \left(\frac{I_{illum} - I_{dark}}{I_{dark}}\right) \times 100 \tag{3}$$

$$D = \frac{\sqrt{AR_{UV}}}{\sqrt{2 \times q \times I_{dark}}} \tag{4}$$

The UV response and saturation behaviour of Sn (NPs)-PANI/Al-IDE/Glass, device is shown in Fig. 5. The µ-IDE structure was subjected to a bias of -1 V to see the maximized effect of UV illumination (wavelength 254 nm and power 300  $\mu$ W/cm<sup>2</sup>) in the reverse bias, and the current was scrutinized by turning the UV light ON and OFF at regular intervals of time ( $\sim 50$  s). Here, the rise time and the fall time are defined as the time taken by the current to increase from 10 to 90% and decrease from 90 to 10% of its final value, respectively [4]. From Fig. 5, the rise time and fall time are estimated to be  $\sim 0.7$  s and  $\sim 1.72$  s, respectively. Therefore, the response of Sn (NPs)-PANI/Al-IDE/Glass, µ-IDE structure is acceptable and comparable to other photodetectors which proves its potential candidature for UV-C detection applications. Furthermore, the performance of state-of-the-art photodetectors as reported in the literature is summarized in Table 1.

Moreover, for real world photodetector applications, the photodiode must have good thermal stability and reliability.



Fig. 5 Current–Time (I-T) characteristics of Sn(NPs)-PANI/Al-IDE/Glass,  $\mu$ -IDE structure at -1 V bias, where the UV light is illuminated after alternate 50 s

	Applied bias	Structure	Preparation method	Responsivity (A/W)	Sensitivity	Detectivity	Refs
1	5 V	Ag/V <sub>2</sub> O <sub>5</sub> /Ag	Spray Pyrolysis	0.948	26,096	-	[64]
2	1.8 V	ZnO nanorods	Hydro-thermal	0.0248	_	_	[ <mark>17</mark> ]
3	2 V	Ge nanowires	VLS methos	1.75	_	_	[65]
4	5 V	NiO film	Sputtering	4.5	6400	_	[66]
5	0.5 V	Single layer graphene- TiO <sub>2</sub> nanotube array	Hydro-thermal	0.126	-	3.3e+11	[19]
6	1 V	Sn(NPs)-PANI	Chemical route	3.02	228514.3	2.26E+13	This work

 Table 1
 Comparison of State-of-the-art photodetector



Fig. 6 Current density–voltage (J–V) characteristics of Sn(NPs)-PANI/Al-IDE/Glass, structure with variation in temperature of 25 °C, 50 °C, 75 °C and 100 °C

Thus, the thermal stability analysis of Sn(NPs)-PANI/Al-IDE/Glass,  $\mu$ -IDE structure is performed from 25 °C to 100 °C. Figure 6 shows the current density–voltage (J-V) characteristics of  $\mu$ -IDE structure with variation in temperature of 25 °C, 50 °C, 75 °C and 100 °C. As revealed from Fig. 6, the current density of the  $\mu$ -IDE array structure increases with increase in temperature. The amount of increase in the current density is in bearable range and hence it establishes the candidature for real world applications.

Figure 7 shows the TEM images of the as-prepared Sn(NPs) and the Sn (NPs)-PANI composite. It can be clearly seen that the Sn(NPs) with an average particle size of ~1.5 to ~3 nm are uniformly dispersed. The uniform distribution and size of Sn(NPs) nanoparticles may be due to one step synthesis with the appropriate and lower concentration of the surfactant and the reducing agent. The crystal lattice fringes of Sn(NPs) particles are clearly detected and the average distance between adjacent lattice planes is ~0.29 nm, corresponding to the (200) plane of crystalline Sn(NPs) [46, 67].

The atomic weight (%) of Sn nanoparticles in Sn(NPs)-PANI is confirmed by the EDX analysis. The computed elemental atomic weight% of Sn(NPs) in Sn(NPs)-PANI composite is  $\sim 7.73\%$  in the polymer matrix.

The effect of doping on the crystallinity of Polyaniline is investigated by the phase analysis of pure polyaniline and Sn(NPs)-PANI by XRD diffractograms as shown in Fig. 8. For the PANI, the characteristic peaks appear at 15.1°, 20.4°, 25.43° corresponding to the (011), (020), and (200) crystalline planes, respectively. Similar results are reported by Li Tang et al. [68]. It can be clearly observed that the (200), (101), (220) and (211) phases of Sn nanoparticle are dominantly present in the Sn(NPs) PANI composite confirming the tetragonal phase of Sn [69]. The peak at 16.8° depicts the presence of SnO<sub>x</sub> content [31]. Here, the increase in crystallinity may be due to the encapsulation of Sn(NPs) in the polyaniline.

Here, device operational model is proposed and schematically presented in Fig. 9(a) along with band diagram in Fig. 9(b). In the Sn (NPs)-PANI composite thin film, the PANI is in the emeraldine base form. The encapsulation of high optical density (10-12) w.r.t carbon, Sn (NPs) in PANI results the conduction path to the µ-IDE array since they act as nano conducting electrode for charge transport [70]. When the composite is illuminated to UV light of  $\lambda \sim 254$  nm surface plasmonics perturbation take place on Sn(NPs) surfaces and result in the electron hole pairs generation in the nano metallic system due to decaying surface plasmonic response [71]. These excited (hot) electrons normally occupy available empty states in the nano metallic system and then get transferred to the polymer (LUMO) states of the hybrid system as shown in Fig. 9(b) [20, 51, 66]. Therefore, the enhanced current density of Sn(NPs)-PANI/Al-µIDE/Glass, in the illumination of  $\lambda \sim 254$  nm light exposure, is attributed to the higher optical density and surface perturbation plasmons resonance at Sn(NPs) nano metallic surfaces as compared to the dark. The hybrid of Sn(NPs) nano metallic with conducting polymer PANI, paves the conduction paths



Fig. 7 TEM images of the prepared samples (a, b) Sn(NPs) nanoparticles prepared by water-in-oil emulsion techniques (c, d) Sn(NPs)-PANI composite in which nanoparticles are capped inside the fibre of polyaniline

to derive the generated charge carriers as shown Fig. 9(b) to the - $\mu$ -IDE's electrodes array. Even though, the diffusion length in the conducting polymer are <10 nm [72], only the charge carriers generated near the electrode might be extensively contribute to the Sn(NPs)-PANI/Al- $\mu$ IDE/Glass photocurrent. In order to utilize the maximum charge carriers generated, the geometry of the  $\mu$ -IDE electrodes array critically play an important role. It has been reported that the larger the  $\mu$ -IDE's electrodes array area the more will be the photo current [57]. Therefore, in the present work, ~50% of the  $\mu$ -IDE's electrodes array area in order to collect the maximum amount of the photocurrent generated at the time of exposure without hampering the sensitivity of the detector is utilized.

#### 4 Conclusion

In Summary, sub-5 nm Sn Nanoparticles (Sn(NPs)) are synthesised with water-in-oil (W/O)  $\mu$ -emulsion technique and encapsulated in Polyaniline by chemical polymerisation. The composite is integrated with the low cost, facile process based  $\mu$ -IDE array to fabricate UV-C detector. TEM and EDAX analysis confirms the uniformly dispersed ~ 1.5 to ~ 3 nm Sn(NPs) encapsulate with Polyaniline and composition ~ 7.73%, respectively. The fabricated Sn(NPs)-PANI/Al-IDE/Glass structures are found highly sensitive to UV-C with a considerable higher photo-todark current contrast ratio of ~ 2290 at -1 V, large responsivity of ~ 3.05 A/W, photoconductive gain of ~ 12.6, reasonable rise/fall time of ~ 0.7/1.7 s and large sensitivity



Fig. 8 XRD of the prepared samples a Polyaniline without nanoparticles. b Sn(NPs) -PANI composite



Fig.9 a Schematic for the charge transfer process within the Sn(NPs)-PANI composite b Energy band diagram under UV illumination of 254 nm wavelength

of  $\sim 228514.3$  which establishes the device as a potential alternate for the UV-C Photodetection applications.

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# References

- M. Martens, J. Schlegel, P. Vogt, F. Brunner, R. Lossy, J. Würfl, M. Weyers, M. Kneissl, Appl. Phys. Lett. 98, (2011)
- J. Yamaura, Y. Muraoka, T. Yamauchi, T. Muramatsu, Z. Hiroi, Appl. Phys. Lett. 83, 2097 (2003)
- F. Omnès, E. Monroy, E. Muñoz, and J.-L. Reverchon, Int. Soc. Opt. Photon., 6473, 64730E (2007)
- S. Sharma, R. Khosla, D. Deva, H. Shrimali, S.K. Sharma, Sensors Actuators, A Phys. 261, 94 (2017)
- J. Agrawal, T. Dixit, I.A. Palani, M.S. Ramachandra Rao, V. Singh, J. Phys. D. Appl. Phys. 51, (2018)
- P. Mukhopadhyay, M. Toporkov, W.V. Schoenfeld, Proc. SPIE
  Int. Soc. Opt. Eng. 10533, (2018)
- B. Albrecht, S. Kopta, O. John, L. Kirste, R. Driad, K. Kohler, M. Walther, O. Ambacher, Jpn. J. Appl. Phys. 52, 6 (2013)
- S. Kang, U. Chatterjee, D.Y. Um, Y.T. Yu, I.S. Seo, C.R. Lee, ACS Photon. 4, 2595 (2017)
- N. Biyikli, I. Kimukin, O. Aytur, E. Ozbay, IEEE Photonics Technol. Lett. 16, 1718 (2004)
- F. Guo, B. Yang, Y. Yuan, Z. Xiao, Q. Dong, Y. Bi, J. Huang, Nat. Nanotechnol. 7, 798 (2012)
- F. Mendoza, V. Makarov, B.R. Weiner, G. Morell, Appl. Phys. Lett. 107, (2015)

- M.M. Fan, K.W. Liu, X. Chen, Z.Z. Zhang, B.H. Li, H.F. Zhao, D.Z. Shen, J. Mater. Chem. C 3, 313 (2015)
- A. Knigge, M. Brendel, F. Brunner, S. Einfeldt, A. Knauer, V. Kueller, M. Weyers, Phys. Status Solidi Curr. Top. Solid State Phys. 10, 294 (2013)
- 14. T. Oshima, T. Okuno, N. Arai, N. Suzuki, H. Hino, S. Fujita, Jpn. J. Appl. Phys. 48, (2009)
- Y. Jin, J. Wang, B. Sun, J.C. Blakesley, N.C. Greenham, Nano Lett. 8, 1649 (2008)
- D.S. Annis, D.F. Mosher, D.D. Roberts, Nat. Nanotechnol. 27, 339 (2009)
- 17. S. Singh, S.H. Park, Optik (Stuttg). 137, 96 (2017)
- 18. A.A. Hussain, A.R. Pal, D.S. Patil, Org. Electron. 15, 2107 (2014)
- D.Y. Zhang, C.W. Ge, J.Z. Wang, T.F. Zhang, Y.C. Wu, F.X. Liang, Appl. Surf. Sci. 387, 1162 (2016)
- 20. T. Barman, A.R. Pal, ACS Appl. Mater. Interfaces 7, 2166 (2015)
- 21. M. Baro, A.A. Hussain, A.R. Pal, RSC Adv. 4, 46970 (2014)
- 22. A.A. Hussain, A.R. Pal, D.S. Patil, Appl. Phys. Lett. 104, (2014)
- 23. X. Feng, C. Mao, G. Yang, W. Hou, J.J. Zhu, Langmuir 22, 4384 (2006)
- 24. Y. Qiao, C.M. Li, S.-J. Bao, Q.-L. Bao, J. Power Sources **170**, 79 (2007)
- 25. J. Zheng, X. Ma, X. He, M. Gao, G. Li, Procedia Eng. 27, 1478 (2012)
- X. Wang, K. Liu, X. Chen, B. Li, M. Jiang, Z. Zhang, H. Zhao, D. Shen, ACS Appl. Mater. Interfaces 9, 5574 (2017)
- K.W. Liu, M. Sakurai, M.Y. Liao, M. Aono, J. Phys. Chem. C 114, 19835 (2010)
- Y. Liu, X. Zhang, J. Su, H. Li, Q. Zhang, Y. Gao, Opt. Express 22, 30148 (2014)
- J.M. McMahon, S.K. Gray, G.C. Schatz, Phys.Chem.Chem.Phys 15, 51415 (2009)
- P. Dou, Z. Cao, C. Wang, J. Zheng, X. Xu, Appl. Surf. Sci. 404, 342 (2017)
- C. Nayral, E. Viala, P. Fau, F. Senocq, J.C. Jumas, A. Maisonnat, B. Chaudret, Chem. - A Eur. J. 6, 4082 (2000)
- 32. D.G. Hermans Sophie, R. Roberts, J.M. Thomas Brain, F.G. Johnson, G. Sarkar, Wiley 113, 1251 (2001)
- 33. M.H. Bhagat, J. Nanosci. Curr. Res. 3, (2018)
- U. Backman, J.K. Jokiniemi, A. Auvinen, K.E.J. Lehtinen, J. Nanoparticle Res. 4, 325 (2002)
- R. Mueller, L. M\u00e4dler, S.E. Pratsinis, Chem. Eng. Sci. 58, 1969 (2003)

- A. Sobhani-nasab, M. Rahimi-nasrabadi, H. Reza, V. Pourmohamadian, F. Ahmadi, M. Reza, H. Ehrlich, Ultrason. - Sonochemistry 45, 189 (2018)
- H. Reza, A. Sobhani-nasab, M. Rahimi-nasrabadi, M. Reza, Appl. Surf. Sci. 423, 1025 (2017)
- M. Rahimi, N. Saeid, M. Kourosh, J. Mater. Sci. Mater. Electron. 28, 16133 (2017)
- S. Grimm, M. Schultz, S. Barth, R. Müller, J. Mater. Sci. 32, 1083 (1997)
- 40. A. Tavakoli, M. Sohrabi, A. Kargari, Chem. Pap. 61, 151 (2007)
- 41. A. Khoshroo, L. Hosseinzadeh, A. Sobhani-nasab, M. Rahiminasrabadi, J. Electroanal. Chem. **823**, 61 (2018)
- J. Amani, M. Maleki, A. Khoshroo, A. Sobhani-nasab, M. Rahiminasrabadi, Anal. Biochem. 548, 53 (2018)
- H. Gu, R. Zheng, X.X. Zhang, B. Xu, J. Am. Chem. Soc. 126, 5664 (2004)
- 44. B.C. Sih, M.O. Wolf, Chem. Commun. 27, 3375 (2005)
- J. Qu, Int. J. Electrochem. Sci. Int. J. Electrochem. Sci. 1106, 4389 (2016)
- 46. S.S. Chee, J.H. Lee, Thin Solid Films 562, 211 (2014)
- 47. Y.H. Jo, I. Jung, C.S. Choi, I. Kim, H.M. Lee, Nanotechnology 22, (2011)
- Y. Ju, T. Tasaka, H. Yamauchi, T. Nakagawa, Microsyst. Technol. 21, 1849 (2015)
- 49. J. Xing, C. Zhao, E. Guo, F. Yang, IEEE Sens. J. 12, 2561 (2012)
- X. Gu, M. Zhang, F. Meng, X. Zhang, Y. Chen, S. Ruan, Appl. Surf. Sci. 307, 20 (2014)
- 51. F. Molina-Lopez, D. Briand, N.F. De Rooij, Sensors Actuators, B Chem. 166–167, 212 (2012)
- 52. M. Soni, T. Arora, R. Khosla, P. Kumar, A. Soni, S.K. Sharma, IEEE Sens. J. 16, 1524 (2016)
- 53. F. Alexander, D.T. Price, S. Bhansali, J. Phys. Conf. Ser. 224, (2010)
- 54. J.B.D. Soole, H. Schumacher, IEEE J. Quantum Electron. 27, 737 (1991)
- J. Hetterich, G. Bastian, N.A. Gippius, S.G. Tikhodeev, G. von Plessen, U. Lemmer, IEEE J. Quantum Electron. 43, 855 (2007)

- C.H. Lei, A. Das, M. Elliott, J.E. Macdonald, M.L. Turner, Synth. Met. 145, 217 (2004)
- 57. J. Ferrer, J. Alonso, S. de Ávila, Sensors 14, 4484 (2014)
- J.W. Jeong, J.W. Huh, J.I. Lee, H.Y. Chu, J.J. Pak, B.K. Ju, Thin Solid Films 518, 6343 (2010)
- J.C. Carrano, T. Li, P.A. Grudowski, C.J. Eiting, R.D. Dupuis, J.C. Campbell, J. Appl. Phys. 83, 6148 (1998)
- C.D. Lokhande, S.S. Kale, U.S. Jadhav, B.G. Wagh, Thin Solid Films 277, 5 (1996)
- S.C.K. Misra, M.K. Ram, S.S. Pandey, B.D. Malhotra, S. Chandra, Appl. Phys. Lett. 61, 1219 (1992)
- M. Das, S. Sarmah, D. Sarkar, Superlattices Microstruct. 101, 228 (2017)
- 63. C.Y. Tsay, P.H. Wu, Ceram. Int. 43, 11874 (2017)
- N.M. Abd-Alghafour, N.M. Ahmed, Z. Hassan, Sensors Actuators A Phys. 250, 250 (2016)
- 65. V. Dhyani, S. Das, Semicond. Sci. Technol. 32, (2017)
- A.A. Ahmed, M. Devarajan, N. Afzal, Sensors Actuators, A Phys. 262, 78 (2017)
- H. Jiang, K.s. Moon, H. Dong, F. Hua, C.P. Wong, Chem. Phys. Lett. 429, 492 (2006)
- 68. L. Tang, F. Duan, M. Chen, RSC Adv. 6, 65012 (2016)
- N. Arora, B.R. Jagirdar, Phys. Chem. Chem. Phys. 16, 11381 (2014)
- X. Feng, Y. Zhang, Z. Yan, Y. Ma, Q. Shen, X. Liu, Q. Fan, L. Wang, W. Huang, J. Solid State Electrochem. 18, 1717 (2014)
- S. Mubeen, G. Hernandez-Sosa, D. Moses, J. Lee, M. Moskovits, Nano Lett. 11, 5548 (2011)
- R. Guntner, U. Asawapirom, M. Forster, C. Schmitta, B. Stiller, B. Tiersch, A. Falcou, H.-G. Nothofer, U. Scherf, Thin Solid Films 417, 1 (2002)

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