A novel ZnO dry etching approach is introduced using reactive ion beam etching of thick sol-gel ZnO layers for controlled nanodisk/nanocone array fabrication. In this approach the same system can be used for the colloidal lithography mask (silica particles) size reduction by a fluorine-based chemistry and etching of the ZnO nanostructures by a CH4/H2/Ar chemistry. This resulted in a ZnO:SiO2 etch selectivity of ~3.4 and etch rate of ~56 nm/min. Thick sol-gel ZnO layers, nanodisk arrays and (truncated) nanocone arrays were fabricated and their optical properties analyzed by finite-difference time-domain simulations and spectrally-resolved total/specular reflectivity measurements. The demonstrated broadband omnidirectional anti-reflection, controlled nanostructure period/geometry and low absorption in the visible-NIR spectrum makes these sol-gel ZnO nanostructures very interesting for many optoelectronic applications, including photovoltaics.

**Fabrication**

Below the fabrication of the nanostructured ZnO films - thick sol-gel ZnO films, colloidal lithography, mask size reduction and RIBE of the ZnO nanostructures - are discussed. The optical properties of the fabricated structures analyzed by FDTD simulation and spectrally resolved total/specular reflectance measurements are presented in the Electromagnetic modeling and simulations section and Optical characterization section.

**Sol-gel ZnO film synthesis.—** For the formation of sol-gel ZnO films, the precursor zinc acetate dehydrate (Zn(CH3COO)2·H2O; Sigma Aldrich) is dissolved in ethanol (C2H6; Sigma Aldrich) and a few drops of diethanolamine (C4H11NO2 (DEA); Sigma Aldrich) is added to it. The resulting solution is then used as the precursor solution for the sol-gel synthesis. The sol-gel synthesis process involves the following steps:

1. Dissolve zinc acetate dehydrate in ethanol.
2. Add a few drops of diethanolamine to the solution.
3. Heat the solution to a temperature of ~80 °C.
4. Allow the solution to cool down to room temperature.
5. Use the sol-gel solution for the formation of ZnO films by spin-coating or dip-coating techniques.

**Optical characterization**

The optical properties of the fabricated ZnO nanostructures are characterized by spectrophotometry and spectrally-resolved total/ specular reflectivity measurements. These measurements are performed using a spectrophotometer and a spectrometer, respectively. The results show that the ZnO nanostructures exhibit broadband omnidirectional anti-reflectivity and low absorption in the visible-NIR wavelength range. The fabricated ZnO nanostructures are attractive for applications in optoelectronics due to their broadband omnidirectional anti-reflectivity and low absorption.
are added to fully dissolve the zinc acetate dehydrate. The solution is stirred at room temperature for at least 1 hour to obtain a uniform solution. Next a drop-cast process in vacuum conditions, by using a desiccator, has been used to produce uniform sol-gel ZnO films, typically ~200–250 nm thick, with homogeneous area coverage on both silicon (Si) and glass substrates. The substrates (~4 cm²) were first cleaned by 5 minutes sonication in acetone and isopropanol, respectively, followed by rinsing with DI water and blow drying with N₂. The surface was treated by oxygen plasma (O₂ flow of 500 sccm, RF power of 1 kW, a pressure of 800 mTorr and reaction time of 10 min) to increase the wettability of the surface. In the next step the sol-gel film was heated at 80°C for 15 minutes, followed by annealing for 1 hour at 300°C to crystallize the ZnO. This resulted in a porous, polycrystalline ZnO single film on the Si surface with a thickness of ~250 nm and a grain size of ~10–20 nm (see Fig. 1a); whereas on glass the layer thickness was lower (~200 nm).

Relatively thick porous sol-gel ZnO films were obtained by repeating the layer formation process several times. Between each deposition the surface was treated by O₂ plasma (reaction time of 5 min) to improve the wettability. The layer which forms on top of a previous layer resulted in an added thickness of ~200 nm. In this work, five sequential layer depositions have been used on Si surfaces and glass, respectively, resulting in approximately 1 μm thick layers (see Fig. 2a).

Figure 1. Characteristics of the sol-gel ZnO layer. (a) shows the top view of the porous polycrystalline ZnO layer fabricated at 300°C. (b) shows the broadband transparency for a ~1 μm sol-gel ZnO layer on glass (in the visible-NIR spectrum).

Figure 2. The fabrication steps of the ZnO nanodisk and (truncated) nanocone arrays. SEM images: (a) representative cross-section showing a fabricated thick porous sol-gel ZnO layer consisting of five sequential layers (indicated by the green lines) on a Si substrate. (b) CL showing the self-assembled SiO₂ colloidal particles. (c) size reduction of the colloidal silica etch mask by CHF₃/Ar-based chemistry by RIBE. The RIBE etching of ZnO is based on CH₄/H₂/Ar chemistry. Inset: longer mask size reduction time. (d) nanodisk array with a 500 nm hexagonal array period, ~250 nm height and ~250 nm diameter. (e) nanopillar array with a 500 nm hexagonal array period, ~700 nm height, ~250 nm top diameter, ~350 nm bottom diameter and ~400 nm bottom ZnO layer. (f) nanocone array with a 500 nm hexagonal array period, ~1100 nm height, top diameter of ~50 nm and bottom diameter of ~500 nm.
A high-resolution X-ray diffraction measurement (HR-XRD; Philips X’Pert mrd) of the ZnO films (see Fig. 3) shows the Zn(002), Zn(101) and Zn(101) peaks; indicating the Wurtzite crystal structure. The vertical axis is given in a logarithmic scaling. Inset: zoom-in on the ZnO peaks for the sol-gel ZnO layer; linear scaling. Representative top-view camera image of: (b) a single sol-gel ZnO layer and (c) a multiple sol-gel ZnO layer stack.

Figure 3. (a) High-resolution X-ray diffraction (HR-XRD) spectrum (20-scan) obtained for a sol-gel ZnO layer (300 °C) of ~250 nm thickness, sputtered ZnO layer of ~1 µm thickness and Si substrate, respectively. The acquisition time/step for the sol-gel ZnO layer was 8 times longer (8s) than for the sputtered ZnO and Si acquisition (1s). For the sol-gel ZnO layer, three ZnO peaks can be observed indicating a Wurtzite crystal structure: ZnO(100), ZnO(002) and ZnO(101). The vertical axis is given in a logarithmic scaling. Inset: zoom-in on the ZnO peaks for the sol-gel ZnO layer; linear scaling. Representative top-view camera image of: (b) a single sol-gel ZnO layer and (c) a multiple sol-gel ZnO layer stack.

Colloidal lithography and mask size reduction.—Colloidal lithography (CL) was used for patterning both the sol-gel and the sputtered ZnO films, and results in self-assembly of SiO2 colloidal particles in a hexagonally close-packed array (see Fig. 2b). A mild spin-coating process of the colloid solution (size 500 nm; Sigma Aldrich) was applied, resulting in close-packed monolayer coverage in several mm² patches on the sample surface. Optimization of the CL process is required to obtain larger (>1 cm²) monolayer area coverages. Before CL a thin (~50 nm) SiO2 layer was deposited on the ZnO film by plasma-enhanced chemical vapor deposition (PECVD) to increase the wettability of the surface to improve the monolayer coverage and to provide a well-defined (additional mask) beneath the silica particles. Before CL the surface was cleaned for 5 minutes in acetone and isopropanol, respectively, followed by rinsing with DI water and blow drying by N2. Oxygen plasma treatment (reaction time of 10 min) was used to further improve the wettability.

An Oxford Instruments Plasma Technology Ionfab 300 Plus tool was used, with a developed CHF3/Ar-based chemistry (CHF3/Ar flow of 10/5 sccm, RF power of 500 W, V acc of 500 V, platen angle of 20° (with regard to perpendicular) and rotation speed of 20 rpm) for the size reduction of the SiO2 colloidal etch mask. The SiO2 mask particles were size reduced to ~370 nm (diameter). The etching is predominantly from the top, with a ‘vertical’ etch rate of ~96 nm/min (see Fig. 2c). An indication of the relation between the etch rate and the resulting colloidal particle diameter was determined, based on this predominantly vertical etching process, and is given in Eq. 1.

\[ D = D_0 \sqrt{1 - \frac{v_{rate} \cdot t}{D_0}} \]  

[1]

Where \( D_0 \) is the original diameter, \( D \) the new diameter, \( v_{rate} \) is the etch rate and \( t \) the etch time.

Additionally the exposed PECVD SiO2 thin layer was etched away, resulting in a cylindrical shaped SiO2 hard mask underneath the SiO2 colloidal particles. This is necessary to avoid undesired etching at the top part of the fabricated nanodisks/cones due to the relatively small contact area of the colloidal particle mask with the underlying surface.

Reactive ion beam etching of ZnO nanostructures.—CH3/He/Ar-based chemistry (with a CH3/He/Ar flow of 2/8/5 sccm, RF power of 500 W, V acc of 500 V, platen angle of 20° (with regard to perpendicular) and platen rotation of 20 rpm) was used for the anisotropic etching of the ZnO nanostructures, resulting in an etch rate of ~51 nm/min and ~30 nm/min and an etch selectivity of ZnO:SiO2 of ~3.4 and ~2 for the sol-gel and sputtered ZnO layers, respectively. Representative SEM images of the etched structures are shown in Fig. 5.

Two types of sol-gel ZnO nanostructures were fabricated: ZnO nanodisk arrays and (truncated) nanocone arrays. The nanodisk array, see Fig. 2d, has a hexagonal array with a period of 500 nm, a height of ~250 nm and a diameter of ~250 nm. The (truncated) nanocone array (Fig. 2e) has a hexagonal array with a period of 500 nm, a height of ~1100 nm, a top diameter of ~110 nm and a bottom diameter of ~500 nm. Figure 2e shows the intermediate etching for the ZnO
nanocone array for which a nanopillar array has a remnant buffer layer. For both the ZnO nanodisks and nanocones the residual SiO$_2$ mask was retained; typical approaches for SiO$_2$ removal (e.g., HF treatment) show poor selectivity between ZnO and SiO$_2$. Spectrally-resolved reflectivity measurements were done for the fabricated ZnO nanodisk/cone arrays (see Fig. 8) and these will be discussed in the Optical characterization section and Discussion section.

Additionally, the fabricated sol-gel ZnO nanostructures/layers can be used as a seed layer for the growth of ZnO nanowires (Fig. 6). Figure 6a shows the ZnO nanowires grown on a (thin) ZnO layer on Si and Fig. 6b shows, as an example, the grown ZnO nanowires on the etched ZnO nanodisks. Previously reported results have shown that such hierarchical ZnO nanowire structures can further reduce the surface reflections, though the growth of these nanowire structures are difficult to control with regard to their specific geometries and spacing and are not suitable for the fabrication of relatively thick pillar arrays. In this work, our focus is on well-defined dry-etched arrays of ZnO nanostructures with typical lateral dimensions much larger than grown nanowires.

**Electromagnetic Modeling and Simulations**

Finite-difference time-domain (FDTD) simulations, using a Lumerical tool, were used for simulating the optical properties (reflection and transmission) of the fabricated ZnO nanodisk/cone array structures. For the ZnO nanodisk array on a c-Si substrate a hexagonal array period of 500 nm, a disk height of 250 nm and a disk diameter of 250 nm were taken and for the (truncated) nanocone array on a c-Si substrate a hexagonal array period of 500 nm, a height of 1100 nm, a top-diameter of 110 nm and a bottom-diameter of 500 nm. In the simulations, a plane wave source, periodic boundary conditions and the known optical constants for bulk ZnO from Palik were used. However, the refractive index of the fabricated ZnO structures could vary with regard to the porosity of the layer. We assume that the porosity is similar in the thick multilayer film. Ellipsometry was used to determine the refractive index of a ~250 nm thick sol-gel ZnO layer on Si and this resulted in a value of $n_{\text{NIR}} \approx 1.76$ in the NIR range; where the refractive index from Palik shows a value of $n_{\text{NIR}} \approx 1.92$. This difference should be taken into account when comparing the data of the simulations (Fig. 8a) and the optical characterization (Fig. 8b). For clarification, the simulation data for the corrected sol-gel refractive index value compared to Palik has been included as inset in Fig. 8a. The data will be further discussed in the Discussion section.

The simulated total reflectance data was determined using a 2D frequency-domain field and power monitor. In addition, simulations of a 250 nm ZnO layer ($n = 1.9–2.2$ for the NIR-visible wavelength range) on a c-Si substrate has been done to compare the anti-reflection properties of the ZnO nanostructures. All the simulated reflectivity results are shown in Fig. 8a. Simulations including the residual SiO$_2$ mask showed minor influence on the reflectivity and its effect is thus neglected in the following.

Additionally, FDTD simulations have been used to determine the optimal geometrical and array dimensions for bulk (and sol-gel; inset in Fig. 7a) ZnO (truncated) nanocone arrays on a c-Si substrate for optimal anti-reflection characteristics. For this the hexagonal array period was varied between 500–2000 nm, the height between 500–1500 nm, the top-diameter between 0–500 nm and the bottom-diameter between 50–500 nm. These simulations resulted in an optimal structure consisting of a hexagonal array period of 500 nm, a height of 600 nm, a top-diameter of 50 nm and a bottom-diameter of 500 nm. A 100 nm ZnO buffer layer underneath the (truncated) nanocone structures minimizes the surface reflection further and results in total reflectance values as low as ~0–5% in the wavelength range of 450–800 nm (see Fig. 7a). The schematic for the optimal structure is shown in Fig. 7b.

**Optical Characterization**

The Si substrate and ZnO films on Si were characterized by spectrally-resolved total reflectivity measurements (spot size

---

**Figure 5.** SEM images showing the comparison of etch rates for the same etch conditions, with in (a) the sol-gel (inset: higher magnification) and in (b) the sputtered ZnO etched layer (inset: higher magnification). These results show an etch rate of ~51 nm/min and ~30 nm/min for the sol-gel and sputtered ZnO layer, respectively.

**Figure 6.** Hydrothermal growth (2 h; 90°C) of ZnO nanowires from a sol-gel ZnO seed surface. SEM images: (a) grown from a thin sol-gel ZnO layer on a Si substrate; Inset: top-view. (b) grown from the surface of the sol-gel ZnO nanodisk array on a Si substrate; Inset: top-view.
Figure 7. Optimal anti-reflection (truncated) nanocone array structure. (a) FDTD simulation results for a (truncated) nanocone array with a 500 nm hexagonal array period, 600 nm height, 50 nm top diameter, 500 nm bottom diameter and 100 nm ZnO bottom layer, where the optical constants for bulk ZnO have been used; Inset: the corrected ‘sol-gel’ ZnO results. (b) Optimal structure derived from simulations.

~9 mm² using a Lambda 950 UV/Vis/NIR spectrophotometer equipped with an integrating sphere; the wavelength range was 300–850 nm. The reflectivity data for the nanocone/disk arrays were obtained using an in-house specular reflection setup (using a supercontinuum source, fiber, lens system and Si detector; the wavelength range was 400–1000 nm) with a spot size of ~900 µm², compatible with typically obtained areas (~1 mm²) with monolayer coverage in CL. The simulated and the measured reflectivity data are shown in Figs. 8a and 8b, respectively, for the wavelength range of 400–850 nm.

The same spectrophotometry setup, as for the spectrally-resolved total reflectivity measurement, was used for the transmittance/absorption measurements (spot size of ~3 mm²) for the ~1 µm thick ZnO film on the glass substrate. The transmittance result for this sample is shown in Fig. 1b. From this it can be concluded that the sol-gel ZnO shows a low to no absorption (total reflectance ~8%) in the wavelength range of 400–850 nm. A rough estimate for the optical bandgap of ~3.5 eV for the sol-gel ZnO was obtained.

Discussion

A sol-gel method has been used to obtain (relatively) thick ZnO films. This approach provides the flexibility to fabricate thick ZnO films from sequential ZnO layer depositions. By tuning/optimizing the settings of the sol-gel process for the separate layer deposition, e.g., deposition volume, viscosity of precursor solution, (air) pressure

during deposition/drying, surface conditions (hydrophilicity) of the substrate and drying temperature, a single layer with a predetermined layer thickness can be tailored. Here five sequential layer depositions, each ~200 nm thick, were used to fabricate a total layer thickness of ~1 µm on Si and glass; where the first layer on Si had a thickness of ~250 nm. Furthermore, instead of drop-casting, very thin ZnO layers can be obtained by spin-coating for which the layer thickness was found to be ~20–30 nm for a spin rate of 3000 rpm.

From the refractive index relation $n_1 = \sqrt{(n_0 \cdot n_s)}$ for a Rayleigh’s film on Si, with $n_0 = n_{air} \approx 1$ and $n_s = n_{Si} \approx 3.7$, the total reflection can be minimized with a film with a refractive index of $n_1 \approx 1.9$. This makes the sol-gel ZnO (n ≈ 1.76 in the NIR wavelength range) a very promising candidate for anti-reflection and in general light manipulation functions on most semiconductor materials (Si, III-Vs, etc.). The nanostructuring of the ZnO film(s) enables optical guiding by refractive index engineering. For this the geometry and array spacing can be tuned for optimizing the material-light interaction for the desired wavelength range.

Dry etching of ZnO layers has been reported for inductively coupled plasma reactive ion etching (ICP-RIE) using CH₄/H₂/Ar-, Cl₂/H₂/Ar- and Cl₂/Ar- based chemistries. Previous work concluded that the ICP-RIE etching with CH₄/H₂/Ar-based chemistry shows the highest etch rates due to the higher volatility of the etch products. For the etching of ZnO by CH₄- and Cl₂-based chemistries the etch products are typically (CH₃)₂Zn and ZnCl₂, respectively.
where the reported vapor pressure for the (CH₃)₂Zn is 301 Torr at 20°C and for ZnCl₂, 1 Torr at 428°C. Thus the etch rate drastically decreases with Cl₂ concentration in the Cl₂-based chemistry. However, for the CH₄-based chemistry the etch rate increases for a higher CH₄ concentration and an etch rate as high as ~280 nm/min has been reported.³⁸ The work by Guo et al.³² using RIE, with CH₄/H₂-based chemistry, showed that the etch rate of ZnO strongly depends on the gas pressure and composition. It is suggested that a volatile metallicorganic zinc compound is formed and that the ZnO etch rate linearly increases with RF plasma power. The highest etch rate reported in that work is ~130 nm/min.

Other chemistries for ICP-RIE etching of ZnO have been reported.³⁹ For example, BCl₃/Cl₂/Ar- and BCl₃/Ar-based chemistries with highest etch rates up to ~100 and ~130 nm/min, respectively. By using only BCl₃ plasma an etch rate of ~150 nm/min was obtained. The BCl₃ chemistry shows to be more effective in etching compared to Ar and Ar/Cl₂. This is attributed due to the higher volatility of the byproducts, e.g., BOCI (BOCl₁) and BO₂. However due to the presence of B-Cl residues, an additional buffered oxide etch (BOE) treatment is necessary.

Work by Kim et al.⁴¹ reports on CF₄/Ar etching of ZnO with a highest etch rate of ~150 nm/min with a relatively low ICP power compared to previous works. The non-volatile by-product of Zn(CF₃)₂ synthesized during the etching process are removed by Ar⁺-ion bombardment.

Joo et al.⁴⁷ report on ICP-RIE etching of ZnO by N₂/Cl₂/Ar-based chemistry. The obtained etch rate and the selectivity to SiO₂ were ~110 nm/min and ~3.2, respectively. The N₂ gas had a positive effect due to the formation of N₂O gases by-products.

In this work, a different approach has been used to dry etch ZnO layers by RIBE. The advantage of this approach is that the same tool can be used for the size reduction of the ZnO etch mask. For the (hard) mask fabrication a combination of SiO₂ colloidal particles (by CL) and a thin SiO₂ layer (deposited by PECVD) underneath was used. The original diameter of the colloidal particle determines the hexagonal array period and the colloidal particle size reduction by CHF₃/Ar chemistry, determines the diameter of the etch mask. A CH₃/H₂/Ar-based chemistry was used for the etching of the ZnO layer due to the advantages noted from previous work discussed above, e.g., high volatility (CH₃)₂Zn by-products, easy to handle and less toxic and corrosive than chloride and bromide gases. Important factors for the tuning of the RIBE process for the ZnO layer etching were the ZnO:mask selectivity, etch rate and anisotropy. The RIBE tool provides the possibility to combine chemical and physical etching; resulting in the etching of well-defined nanostructures. A further advantage is that the sample stage can be tilted/rotated, providing an additional flexibility and control for etch direction/shaping.

In this work, a compromise was made between the etch selectivity and the etch rate and the aim was not to obtain the highest etch rate. For comparison a sputtered ZnO layer was used for etching, resulting in a lower etch rate (~30 nm/min) than for the sol-gel ZnO (~51 nm). The higher etch rate for the sol-gel ZnO is most likely due to the porous nature of the layer.

The spectrally-resolved reflectivity measurements (wavelength range 300–850 nm) by spectrophotometry and the FDTD simulations show similar results (see Fig. 8). For the simulations both bulk and ‘sol-gel’ ZnO refractive index data (obtained by ellipsometry) were used for the structures. Due to the lower refractive index, the sol-gel ZnO results show a slight (red)shift of the spectrum and the reflectance is observed to be, on average, ~2% higher compared to bulk. The ZnO Rayleigh’s film (~250 nm) shows an average total reflectivity of ~20–30% and shows a Fabry Perot-effect. The simulated data for the ZnO nanodisk array shows an average reflectivity of ~15–20% with dips at wavelengths around ~433 nm and ~510 nm due to the array period and Mie resonances (related to the diameter of the nanodisks), respectively. The lack of dips due to Mie resonances for the fabricated nanodisk array is most likely due to disk diameter variations due to the SiO₂ particle sizes and further process-induced variations. The ZnO (truncated) nanocone array, shows an average total reflectivity of ~5–10% and has the lowest measured surface reflection. Additional simulation data for an optimal structure for the ZnO (truncated) nanocone array on Si shows that the surface reflection can be further minimized to ~0–5% for the wavelength range 450–800 nm (see Fig. 7).

The broadband omnidirectional anti-reflectivity and low absorption of the well-defined ZnO nanostructures makes them very interesting for optoelectronic applications, e.g., solar cells and photodetectors. In addition, these highly transparent (optical guiding) structures could be useful for LED applications. Furthermore the sol-gel ZnO porous nature and possibility for hierarchical ZnO structuring could also make these structures interesting for (bio/gas) sensing and photo catalysis.

**Conclusions**

A flexible method is introduced using the fabrication of relatively thick sol-gel ZnO films (up to ~2 µm) on silicon (Si) which is used for the RIBE etching of well-defined ZnO nanostructures having a good control over their periodicity and nanostructure geometry. This cheap and easy method is interesting since the sol-gel layers can be applied on a variety of substrates. Both the lithography-mask size reduction step and the ZnO etching were performed in the etching chamber. A colloidal lithography method using SiO₂ colloidal particles was applied to pattern the surface with a close-packed hexagonal array. CHF₃/Ar-based chemistry was used for size reducing the SiO₂ mask. RIBE, using a CH₃/H₂/Ar-based chemistry, was used to etch the ZnO films resulting in a ZnO:SiO₂ selectivity of ~3.4 and an ZnO etch rate of ~51 nm/min. The sol-gel ZnO etch rate is significantly higher compared to that of sputtered ZnO (~30 nm/min). Sol-gel ZnO nanodisk arrays, (truncated) nanocone arrays and planar layer(s) were fabricated on Si-substrates and optically characterized for their spectral dependent surface reflectivity. The fabricated nanodisk array has a hexagonal array period of 500 nm, a height of ~250 nm and a diameter of ~250 nm. The fabricated (truncated) nanocone array has a hexagonal array period of 500 nm, height of ~1.1 µm and top-bottom diameter of ~110–500 nm.

The reflectivity data obtained from FDTD simulations and spectrophotometry measurements show similar results. For the nanodisk array on Si average reflectivity of ~15–20%, in the wavelength range of 400–850 nm, and for the (truncated) nanocone array on Si reflectivity as low as ~5–10% were obtained. Simulations regarding the optimal anti-reflective ZnO (truncated) nanocone array structuring on a Si surface indicate further reduction in reflectivity, as low as ~0–5% over the wavelength range of 450–800 nm.

The broadband omnidirectional anti-reflectivity and low absorption makes the sol-gel ZnO nanostructures very interesting for optoelectronic applications, e.g., solar cells, photodetectors and LEDs. In addition, this sol-gel ZnO (nano)structuring could be useful for (bio/gas) sensing and photo catalysis applications due to its porous nature and high surface-to-volume ratios.

**Acknowledgments**

The authors like to acknowledge the support from the Linné center for advanced optics and photonics (ADOPT), the Swedish Research Council (VR), the Swedish Energy Agency (Energimyndigheten) and the Department of Science and Technology (DST), India.

**References**

1. S. J. Pearton, D. P. Norton, K. Ip, and Y. W. Heo, “Recent advances in processing of ZnO,” J. Vac. Sci. Technol. B, 23(1), 932 (2004).
2. U. Özgür, Ya. I. Alivov, C. Liu, A. Teke, M. A. Reshchikov, S. Dogan, V. Avrutin, S.-J. Cho, and H. Morkoc, “A comprehensive review of ZnO materials and devices,” J. Appl. Phys., 98, 041301 (2005).
3. P. F. Carcia, R. S. McLean, M. H. Reilly, and G. Nunes Jr., “Transparent ZnO thin-film transistor fabricated by rf magnetron sputtering,” Appl. Phys. Lett., 82, 1117 (2003).
4. Z. L. Wang and J. Song, “Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays,” Science, 312(5771), 242 (2006).
5. C. S. Rout, A. R. Raju, A. Govindaraj, and C. N. R. Rao, “Hydrogen sensors based on ZnO nanoparticles,” Solid State Communications, 138, 136 (2006).
6. M.-K. Lee, C.-L. Ho, and P.-C. Chen, “Light Extraction Efficiency Enhancement of GaN Blue LED by Liquid-Phase-Deposited ZnO Rods,” IEEE Photonic Technology Letters, 20(4), 252 (2008).
7. J.-Y. Chen and K. W. Sun, “Growth of vertically aligned ZnO nanorod arrays as antireflection layer on silicon solar cells,” Solar Energy Materials & Solar Cells, 94, 930 (2010).
8. S. K. Arya, S. Saha, J. Ramirez-Vick, V. Gupta, S. Bhansali, and S. P. Singh, “Recent advances in ZnO nanostructures and thin films for biosensor applications: Review,” Analytica Chimica Acta, 737, 1 (2012).
9. W. Wang, Q. Zhao, J. Xu, and D. Yu, “A unique strategy for improving top contact in Si/ZnO hierarchical nanoheterostructure photodetectors,” CrystEngComm, 14, 3015 (2012).
10. J.-U. An, H. J. Yun, K. S. Jeong, Y.-M. Kim, S. D. Yang, S. H. Kim, J. S. Kim, Y. U. Ko, H. D. Lee, and G. W. Lee, “Improvement in n-ZnO/p-Si diode properties using ZnO/AZO homogeneous metal contact,” Jpn. J. Appl. Phys., 53, 08N303 (2014).
11. J. Lu, S. X. Lim, and C. H. Sow, “A Focused Laser Beam: A Useful and Versatile Tool for 1D Nanomaterials Research: A Review,” J. Mater. Sci. Technol., 31, 616 (2015).
12. F. Teng, L. Zheng, K. Hu, H. Chen, Y. Li, L. Zhang, and Z. Fang, “A surface oxide thin layer of copper nanorods enhanced the UV selective response of a ZnO film photodetector.” J. Mater. Chem. C, 4, 8416 (2016).
13. Y. H. Liu, S. J. Chang, and S. J. Young, “Enhanced Field Emitter Base on Indium-Doped ZnO Nanostructures by Aqueous Solution,” ECS J. Solid State Sci. Technol., 5, R203 (2016).
14. B. Zhao, F. Wang, H. Chen, L. Zheng, L. Su, D. Zhan, and X. Fang, “An Ultra-high Responsivity (9.7 mA/W) Self-Powered Solar Blind Photodetector Based on Individual ZnO-Ga2O3 Heterostructures,” Adv. Funct. Mater., 27, 1700267 (2017).
15. A. K. Sood, Z. L. Wang, D. L. Polla, N. K. Dhar, T. Manzur, and A. F. M. Anwar, “ZnO Nanostructures for Optoelectronic Applications,” Optoelectronic Devices and Properties, O. Seryugin, (Ed.), ISBN: 979-953-307-204-3, InTech, (2011); Available from: http://www.intechopen.com/books/optoelectronic-devices-and-properties/zno-nanostructures-for-optoelectronic-applications
16. A. B. Djurisić, A. M. C. Ng, and X. Y. Chen, “ZnO nanostructures for optoelectronics: Material properties and device applications,” Progress in Quantum Electronics, 34(4), 191 (2010).
17. X. Wang, J. Zhou, J. Song, J. Liu, N. Xu, and Z. L. Wang, “Piezoelectric Field Effect Transistor and Nanoforce Sensor Based on a Single ZnO Nanowire,” Nano Lett., 6(12), 2768 (2006).
18. S. Chattopadhyay, Y. F. Huang, Y. J. Jen, A. Ganguly, K. H. Chen, and L. C. Chen, “Anti-reflecting and photonic nanostructures,” Materials Science and Engineering B, 99, 1 (2010).
19. W. Gao and Z. Li, “ZnO thin films produced by magnetron sputtering,” Ceramics International, 30, 1155 (2004).
20. Q. Li, V. Kumar, Y. Li, H. Zhang, T. J. Marks, and R. P. Chang, “Fabrication of ZnO Nanorods and Nanotubes in Aqueous Solutions,” Chem. Mater., 17, 1001 (2005).
21. D. F. Liu, Y. J. Xiang, Q. Liao, J. P. Zhang, X. C. Wu, Z. X. Zhang, L. F. Liu, W. J. Ma, J. Shen, W. Y. Zhou, and S. S. Xie, “A simple route to scalable fabrication of perfectly ordered ZnO nanorod arrays,” Nano Letters, 18, 40503 (2007).
22. Z. Jing and J. Zhan, “Fabrication and Gas-Sensing Properties of Porous ZnO Nanoplates,” Adv. Mater., 20, 4547 (2008).
23. J. P. Kar, M. H. Ham, S. W. Lee, and J. M. Myoung, “Fabrication of ZnO Nanostructures of various dimensions using patterned substrates,” Applied Surface Science, 255(7), 4087 (2009).
24. S. Zhang, Y. Shen, H. Fang, S. Xu, J. Song, and Z. L. Wang, “Growth and replication of ordered ZnO nanowire arrays on general flexible substrates,” J. Mater. Chem., 20, 10606 (2010).
25. L. Vayssieres, “Growth of Arrayed Nanorods and Nanowires of ZnO from Aqueous Solutions,” Adv. Mat., 15(5), 464 (2003).
26. Y. Alivov, E. V. Kalinaeva, A. C. Cherenkov, D. C. Look, B. M. Aetae, A. K. Omaev, M. V. Chukichev, and D. M. Bagnall, “Fabrication and characterization of n-ZnO/p-AIGaN heterojunction light-emitting diodes on 6H-SiC substrates,” Appl. Phys. Lett., 82, 4721 (2003).