4. RESULTS ON INDIUM OXIDE FILMS

Indium oxide ($\text{In}_2\text{O}_3$) is a wide band gap of (3.4–3.75eV) transparent conducting semiconductor and has C-type rare earth sesquioxide structure with space group $T_h^7$ containing 80 atoms or 16 formula units. This structure is related to a fluorite in which one fourth of all anion sites are structurally vacant [161]. It shows excellent electrical and optical properties suitable for the use as transparent electrodes in devices such as multi-layer solar cells, flat panel displays and photodiodes [162]. In thin film form, their wide range of applications include transparent windows in liquid crystal displays, anti-reflection coatings [163], and optoelectronic and electrochromic devices [164] and has shown remarkable prospects in the field of upcoming nanoelectronic building blocks and nanosensors. The observance of both high optical transmittance and high electrical conductivity simultaneously in Indium oxide makes it a suitable transparent conducting oxide material for many devices developments [165]. $\text{In}_2\text{O}_3$ thin films has been prepared by a variety of techniques such as chemical vapor deposition (CVD) [166], reactive thermal evaporation [167], pulse laser deposition (PLD) [168], ion beam sputtering [169], RF/direct current (DC) magnetron sputtering [170], spray pyrolysis [171] etc. Most of these methods are expensive, involving sophisticated vacuum techniques and hence investigations to find alternative low-cost tools are underway. Amongst them, the sol gel dip coating method is the inexpensive method for depositing films.
In this work, Indium oxide films were deposited on glass substrates by the sol gel dip coating technique using the Acrylamide route for the first time. The films after dip coating were post annealed in the temperature range of 350 - 500°C in air.

Fig. 4.1 shows the X-ray diffraction patterns of the In$_2$O$_3$ thin films formed at different temperature in air. All the peaks in the films correspond to the cubic structure of polycrystalline In$_2$O$_3$ with diffractions from (222), (400), (440) and (622) planes. It can be seen from the diffraction patterns that the samples annealed at 350°C displays weak diffraction intensity peaks. As heat treatment temperature increased, the orientation of (222) crystal plane is predominant. From the diffraction peak positions the lattice constants of In$_2$O$_3$ thin films for different samples were obtained and are presented in Table 4.1. The lattice constant is 1.0118 nm for the bulk In$_2$O$_3$ crystal that has a cubic structure [172]. The larger value of lattice constant obtained for the films formed at lower temperatures indicates that the unit cell is elongated, and compressive force exists in the plane of the film. However, at higher formation temperatures, the lattice constant decreases and is close to the bulk one, which indicates that the compressive strain in the In$_2$O$_3$ films are gradually relaxed as the formation temperature increases and it is almost fully relaxed. The grain size D of the films was calculated using Scherrer’s formula:

$$ D = \frac{0.9 \lambda}{\beta \cos \theta} \quad (4.1) $$
Fig. 4.1 XRD pattern of In$_2$O$_3$ films formed at different temperatures (a) 350°C (b) 400°C (c) 425°C (d) 475°C (e) 500°C
Table – 4.1 Effect of information temperature on the structural properties of \( \text{In}_2\text{O}_3 \) films

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Lattice constant (nm)</th>
<th>Grain size (nm)</th>
<th>Strain (ε) ( \times 10^{-3} )</th>
<th>Dislocation density ( \times 10^{15} ) lines m(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1.0196</td>
<td>1.0</td>
<td>1.63</td>
<td>3.43</td>
</tr>
<tr>
<td>400</td>
<td>1.0175</td>
<td>8.9</td>
<td>1.30</td>
<td>2.23</td>
</tr>
<tr>
<td>450</td>
<td>1.0121</td>
<td>14.5</td>
<td>1.01</td>
<td>1.03</td>
</tr>
<tr>
<td>475</td>
<td>1.0116</td>
<td>17.4</td>
<td>0.88</td>
<td>0.75</td>
</tr>
<tr>
<td>500</td>
<td>1.0113</td>
<td>20.0</td>
<td>0.45</td>
<td>0.33</td>
</tr>
</tbody>
</table>
where $\lambda=0.1540598$ nm and $\beta=(\text{FWHM}-b)$, $b$ is the instrumental broadening ($0.09^\circ$). FWHM is the measured full width at half maximum intensity of the diffraction peak at an angle of $2\theta$. As estimated from the (222) peak, the grain size of the films increase from 7.0 to 20.0 nm with the increase of annealing temperatures from 350°C to 500°C, due to improvement in the crystallinity of the films. The crystals defect parameters like microstrain and dislocation density show a decreasing trend with increase in formation temperature. This type of change in strain may be due to the recrystallization process in the polycrystalline films. At high formation temperatures, both the microstrain and dislocation density are minimum, which reveals the reduction in the concentration of lattice imperfections leading to preferred orientations [173]. The microstrain and dislocation density were calculated using the following relations.

$$\frac{\beta \cos \theta}{\lambda} = \frac{1}{D} + \frac{\varepsilon \sin \theta}{\lambda} \quad (4.2)$$

The plot of $\frac{\beta \cos \theta}{\lambda}$ vs $\frac{\sin \theta}{\lambda}$ allows us to determine strain ($\varepsilon$) from slope of the graph. The dislocation density ($\delta$) was obtained from the following relation

$$\delta = \frac{15\varepsilon}{(aD)} \quad (4.3)$$

The strain, lattice parameters, dislocation density and grain size are shown in Table.4.1.

The EDAX analysis revealed that the nearly stoichiometric films were obtained for the films annealed at temperatures greater than 400°C. The films annealed at
lower temperatures slight excess of Indium was observed. Fig.4.2 shows the EDAX spectrum of the In$_2$O$_3$ films formed at 500°C.

Surface morphology of the films was studied by Atomic force microscopy (Fig.4.3). It is observed from the figures that, the RMS value of the surface roughness increases from 0.15 nm to 1.08 nm with increase of annealing temperature. Fine grains are observed for the films formed at lower temperatures. Higher formation temperatures result in larger grains. The films exhibit a uniform distribution of the grains throughout the entire surface.

Fig.4.4 shows a typical XPS spectrum of indium oxide formed at 500°C. The In$_2$O$_3$ spectrum exhibits the characteristic spin-orbit split 3d$_{5/2}$ and 3d$_{3/2}$ signals and a O 1s peak. The O 1s XPS signals (Fig. 4.4b) could be deconvoluted into two components. This is similar to earlier reports on XPS investigations on In$_2$O$_3$ samples [174–176]. The observed O 1s peak at 530.7 eV to 530.8 eV can be assigned to the lattice oxygen in crystalline In$_2$O$_3$ and O 1s peak at 532.8 - 533.0 eV to adsorbed OH groups or to adsorbed oxygen species (O$^\delta^-$) [174].

It is clearly observed that the transmittance spectra (Fig.4.5) showed interference fringes due to the result of the interference of light reflected between the air/film and film/substrate interfaces. As the formation temperature and the thickness of the film increase, the interference effects also become more prominent. The thickness of the sample measured from the interference maxima and minima values are almost nearer to the values obtained from the stylus
Fig. 4.2 EDS spectrum of In$_2$O$_3$ films formed at 500°C
Fig. 4.3 Atomic force micrograph of Indium oxide films formed at different temperatures (a) 350°C (b) 450°C (c) 500°C
Fig. 4.4 XPS spectra of Indium oxide films formed at 500°C
Fig. 4.5 Transmission spectra of In$_2$O$_3$ films formed at different temperatures (a) 500°C (b) 475°C (c) 425°C (d) 400°C (e) 350°C
profiler. From the measured spectral transmittance, the optical band gap values of polycrystalline In$_2$O$_3$ films are evaluated. The optical absorption are related to the optical band gap $E_g$ of the post heat treated films satisfies the equation:

$$\alpha h \nu = A (h \nu - E_g)^{1/2}$$  \hspace{1cm} (4.4)

The plots of $(\alpha h \nu)^2$ vs. $h \nu$ for the In$_2$O$_3$ films post heated at different temperatures is shown in Fig. 4.6. It can be seen that the plot is linear in the region of strong absorption, i.e. near the fundamental absorption edge. Extrapolation of the linear portion to $(\alpha h \nu)^2 = 0$ gives the direct allowed band gap values for the films. The energy gaps of the films are found to vary from 3.53 to 3.68 eV. Such a shift in band gap to higher energies is attributed to the increased carrier density due to Burstein–Moss effect. This effect is due to the filling of states near the bottom of the lowest state in the conduction band [177]. This high value of band gap confirms the surface smoothness and uniformity of the In$_2$O$_3$ films. The band gap values are in agreement with the already reported In$_2$O$_3$ films prepared by the reactive thermal evaporation technique [178]. These band gap with the order of 3.7 - 3.8 eV are associated with (2 2 2) orientation.

The refractive index was calculated from the transmission graph using the envelope method. The refractive index of the film decreases with the increase of $\lambda$. This is consistent with what one would expect from Kramers Kroning analysis and the refractive index value at 400nm is 1.995, which is very close to the reported value of 2.0 [179]. Further, the refractive index values are found to be lower for the films post heated at lower temperatures. The dispersion relation for
Fig. 4.6 Tauc's plot of In$_2$O$_3$ films formed at different temperatures (a) 500°C (b) 475°C (c) 425°C (d) 400°C (e) 350°C
refractive index fits well and explains the variations obtained for indium oxide films. The variation of refractive index with wavelength is shown in Fig.4.7. The dispersion of refractive index below the interband absorption edge is analyzed using the Wemple and DiDomenico model (W-D model) [180], which is given as

\[ n^2 - 1 = \frac{E_d E_o}{E_o^2 - E^2} \]  

(4.5)

where \( E \) is the photon energy, \( E_o \) is the oscillator energy, and \( E_d \) is the dispersion energy. Wemple and DiDomenico reported that the dispersion energy may depend upon the charge distribution within each unit cell that is closely related to chemical bonding [180]. The oscillator energy \( E_o \) and dispersion energy \( E_d \) are obtained from the slope \((E_o E_d)^{-1}\) and intercept \(E_o / E_d\) on the vertical axis of the straight line portion of \((n^2-1)^{-1}\) versus \(E^2\) plot, respectively [181]. The values of \( E_o \) and \( E_d \) for interband optical transitions are obtained as 7.12 and 16.81 eV, respectively. From these values, the long wavelength limit of refractive index \( n_\alpha \) can be determined using the expression:

\[ n_\alpha = \left( 1 + \frac{E_d}{E_o} \right)^{1/2} \]  

(4.6)

The long wavelength \((1/\lambda_0)\) limit refractive index of the \( \text{In}_2\text{O}_3 \) films heat treated at 500°C was calculated and the obtained value of \( n_\alpha = 1.83 \) is consistent with the reported values [182].

The room temperature electrical resistivity was found to decrease from the value of 40 ohm cm to 15 ohm cm for the films formed in the temperature range 350 – 500°C. Similar results on resistivity variations with deposition temperatures were reported by Girtan and Folcher [183] and Byrant [184] for \( \text{In}_2\text{O}_3 \) thin films.
Fig. 4.7 Variation of refractive index with wavelength for In$_2$O$_3$ films formed at different temperatures (a) 350°C (b) 425°C (c) 475°C (d) 500°C
prepared by ultrasonic spray CVD process. The variations in the measured resistivity values with heat treatment temperature (Fig.4.8) may be due to the film growth mechanism associated with the formation of nuclei and clusters. At the lower heat treatment temperatures, few nuclei are formed due to the availability of lower energy. However, many nuclei are formed at high temperature and the grains are grown by the continuous diffusion leading to an increase in conductivity.

Hot probe measurement and the sign of the Hall coefficient confirms the n-type semiconducting nature of In$_2$O$_3$ films. The effect of formation temperature on carrier concentration and Hall mobility are plotted in Fig. 4.9 and Fig.4.10. It is observed that In$_2$O$_3$ films prepared here have carrier concentration values in the range of $1.67 \times 10^{16}$ to $37.2 \times 10^{16}$ cm$^{-3}$ with increase of formation temperature. Fig. 4.10 shows that the carrier concentration increases with formation temperature.

The Hall mobility variation is also similar to that of carrier concentration. A maximum value of 9.35 cm$^2$/ V s is obtained in the present study, and these values are lower than the previously reported values [185]. The Hall mobility is influenced by the various scattering mechanisms, like grain boundary scattering, ionized impurity scattering, neutral impurity scattering, and scattering at other defects and dislocations [186].

Fig. 4.11 shows the photoluminescence (PL) emission spectrum of indium oxide thin films. Two distinct peaks in the PL spectrum were observed in the blue region, i.e. at wavelengths of 415 and 440 nm wavelengths under the excitation
Fig. 4.8 Variation of room temperature resistivity with formation treatment temperature of Indium oxide films formed at different temperatures.
Fig. 4.9 Variation of room temperature mobility with formation temperature of Indium oxide films formed at different temperatures.
Fig. 4.10 Variation of room temperature carrier concentration with formation temperature of Indium oxide films formed at different temperatures.
Fig.4.11  Room temperature photoluminescence emission spectrum of $\text{In}_2\text{O}_3$ films formed at 500°C
wavelength of 375 nm at room temperature. Lee et al. [187] had observed the photoluminescence at room temperature in orange region for the In$_2$O$_3$ films deposited on Si and Mo substrates. In the literature, strong peaks were observed at 470 and 1540 nm in single crystalline In$_2$O$_3$ films [188] and erbium doped In$_2$O$_3$ films [189], respectively. One of the possible reasons is explained as follows. When the indium oxide films were heated at high temperature, oxygen vacancies and oxygen-indium vacancy pairs might have been produced. Therefore, it is believed that these vacancy pairs might be due to the post heat treatment of Indium oxide films [187].

Raman spectroscopic studies of all the In$_2$O$_3$ films have been performed at room temperature. Characteristic Raman peaks corresponding to indium oxide are observed at 496 and 627 cm$^{-1}$ for all the films. The Raman spectra of indium oxide films formed at different temperatures are shown in Fig.4.12. Indium oxide belongs to cubic C-type rare-earth oxide structure and, for this type of structure, the factor group analysis predicts 4Ag (Raman) + 4Eg (Raman) + 14Tg (Raman) + 5Au (inactive) + 5Eu (inactive) + 16 Tu (i.r.) modes [190]. All the observed modes correspond to band positions reported in literature for cubic indium oxide [191]. Raman spectra and the x-ray diffraction analysis of the indium oxide films thus show the presence of a cubic phase.

All the In$_2$O$_3$ films were sensitized in a dye solution of cis-di (thiocyanate) bis (2, 2'-bipyridyl-4,4'-di-carboxylate) ruthenium (II) (R535, N3-dye, Solaronix) for 12 h at room temperature. Carbon paste coated on a FTO substrate was used as a counter electrode. The Dye sensitized solar cell (DSSC) was fabricated by
Fig. 4. 12 Raman spectra of In$_2$O$_3$ films formed at different temperatures
(a) 350°C (b) 425°C (c) 500°C
clamping the dye-sensitized indium oxide photoelectrode against carbon counter-electrode and filling the inter-electrode space by the electrolyte of 0.5M KI, 0.05M I\textsubscript{2} and 0.05M 4-tert-butylpridine using capillary force. The active cell area was 0.25 cm\textsuperscript{2}. The cell was irradiated with a 250 W Xenon lamp with ultraviolet and an infrared-blocking filter. The intensity of light was 100 mW cm\textsuperscript{-2}.

The important parameter of the DSSC is the photoelectric conversion efficiency. The photoelectric conversion efficiency of solar cells is the ratio of the output power to the incident power. The efficiency (\(\eta\)) of the DSSCs can be calculated from the expression [192]:

\[
\eta = \frac{(J_{SC} V_{OC} FF)}{P_{in}}
\]

where \(J_{SC}\) is the photocurrent, \(V_{OC}\) is the open-circuit voltage, \(FF\) is the fill factor: \(FF = (I\times V)_{max}/J_{SC} V_{OC}\), and the \(P_{in}\) is the intensity of the incident light. Fig.4.13 shows the photocurrent–photovoltage characteristic curve of DSSCs using the indium oxide films annealed at different temperatures. The \(\eta\), \(FF\), \(V_{OC}\), and \(J_{SC}\) of the DSSCs are summarized in Table 4.2. From the figure, it is observed that the DSSC with the indium oxide photoelectrode formed at 500°C, shows the maximum efficiency of 0.86% with the photovoltage of 0.46 V and photocurrent of 2.80 mA cm\textsuperscript{-2}. This efficiency is higher than the efficiency reported by other research groups [193–197].

The performance of the DSSC can be quantified on a macroscopic level in terms of the incident photon to current efficiency (IPCE). The IPCE is the ratio
Fig. 4.13  Photocurrent – photo voltage characteristics of indium oxide photo electrodes formed at different temperatures

(a) 350°C  (b) 450°C  (c) 475°C  (d) 500°C
between the number of generated charge carriers contributing to the photocurrent and the number of incident photons, as given by [198]:

$$IPCE \, (\%) = 1240 \times \frac{J_{SC}}{\lambda \times P_{in}} \times 100 \, \% \quad (4.8)$$

where $\lambda$ is the wavelength of the incident light. Fig.4.14. displays the wavelength distribution of IPCE for the photoelectrode annealed at 500°C. The photocurrent peaks occurring at approximately 410 nm are due to direct-light harvesting by $\text{In}_2\text{O}_3$ semiconductor, in which the photogenerated electrons diffuse through $\text{In}_2\text{O}_3$ and the holes in the valence band are replenished directly by charge transfer from the $\text{I}_3^-/\text{I}^-$ electrolyte [199]. The IPCE value at around 526 nm has contributed by the dye absorption, corresponding to the visible $\tau_2 \rightarrow \pi^*$ metal-to-ligand charge transfer (MLCT). The DSSC shows reasonably high IPCE value. The IPCE spectrum shows two peaks at 410 and 526 nm, which are close to ruthenium-based dye ($\text{N}_3$-dye) absorbance.

**Sensor studies**

Hydrogen sulfide ($\text{H}_2\text{S}$) is an important industrial gas used in the production of inorganic compounds, alkali metal sulfides and analytical chemistry. It is colorless, highly toxic and easily flammable. It has the ability to paralyse one’s sense of smell and the potential victims may be unaware of its leakage until it is too late. Therefore, the detection of the $\text{H}_2\text{S}$ gas, especially at low concentration, is important. In this work, $\text{In}_2\text{O}_3$ films were deposited by the acrylamide sol gel dip coating method and their gas sensing characteristics are
Fig. 4.14 IPCE spectrum of In$_2$O$_3$ film formed at 500°C
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA m$^{-2}$)</th>
<th>ff</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.40</td>
<td>2.40</td>
<td>0.50</td>
<td>0.48</td>
</tr>
<tr>
<td>450</td>
<td>0.42</td>
<td>2.50</td>
<td>0.61</td>
<td>0.64</td>
</tr>
<tr>
<td>475</td>
<td>0.43</td>
<td>2.65</td>
<td>0.67</td>
<td>0.76</td>
</tr>
<tr>
<td>500</td>
<td>0.46</td>
<td>2.80</td>
<td>0.68</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 4.2 Photovoltaic performance of indium oxide photo electrodes formed at different temperatures
studied and presented. Earlier, nanocrystalline In$_2$O$_3$ synthesized by sintering the precursor hydrothermal at 250°C for 24 h, was used as a H$_2$S gas sensor [200]. It was reported that sensors were sensitive at 270°C. J.Tu et.al has reported that Pt doped indium oxide sensors exhibited response at an operating temperature of 150°C [201].

Sensitivity measurements are being characterized by any one of the two methods, dynamic and static system. In the present study, static system is employed, which comprises an airtight chamber with air admittance and gas inlet valves (Fig.2.5). The sensor is placed inside an airtight chamber of known volume 25,000 cm$^3$. The substrate is kept at a chosen temperature using a flat heater and the values of temperature are measured by the Cr–Al thermocouple. Two Al electrodes are used for ohmic contact with the film. Initially, the chamber was evacuated to a base pressure of $10^{-2}$ Torr using a rotary pump and electrical measurements are performed at a temperature (say 100°C) in vacuum. This response is considered as a reference response for the calculation of sensitivity. The temperature is controlled by varying the current flow through the heater and measured with an accuracy of ±1 °C using a temperature controller. After noting the reference response, the test gas is injected inside the bell jar through a needle valve. After injecting the test gas, all the valves are closed to avoid the leakage of test gas. The resistance of the sensor is once again measured at the same temperature in H$_2$S ambient. After completing measurements, the gas is wiped off to carry out next cycle by injecting fresh air into the chamber.
The experimental arrangement for electrical measurements is shown in Fig.2.5. Electrical measurements were performed using a volt-amperometric technique. The sensor mounted on a heater was housed in a closed chamber into which a desired amount of H\textsubscript{2}S gas could be injected. Aluminium contacts (which make ohmic contact to the sample) was used as electrodes for passing current through the sensor. A constant bias voltage of 10 V is applied to the sensor. The voltage across a series resistor $R \ll R_s$, the sensor resistance is measured using a voltmeter having a least count of 1 μV. From these signals, the sensor resistance is calculated for different H\textsubscript{2}S gas concentrations at different operating temperatures. Operating temperatures are fixed by adjusting the supply voltage given to the flat heater. In the present study, the sensitivity is determined by using the relation

$$S = \frac{(R_{\text{vac}} - R_{\text{gas}})}{R_{\text{gas}}}$$  \hspace{1cm} (4.9)

When the sensor is exposed to reducing gases, the variation in resistance for the semiconductor-based sensors is mainly caused by the reaction between the reducing gases and the surface of the semiconductor, which changes with the operating temperature. The temperature dependence of sensitivity of gas is presented in Fig. 4.15. The best response, in case of films post heat treated at 350°C may be because of more available sites for the test gas to be adsorbed. The decrease in response for the films post heat treated at higher temperatures may be due to the insufficient number of sites available on the surface. The partial replacement results in decrease of grain size with increase of surface
Fig. 4.15 Sensitivity of \( \text{In}_2\text{O}_3 \) films formed at different temperatures 350°C (b) 450°C (c) 500°C exposed to \( \text{H}_2\text{S} \) gas (10 ppm) at different operating temperatures of the sensors.
area. Since small grains have relatively large grain boundary areas, the adsorption of \( \text{H}_2\text{S} \) molecules is relatively high.

It is well known that the sensing mechanism of the oxide materials is surface controlled in which the grain size, surface states and oxygen adsorption play an important role [202]. The larger surface area generally provides more adsorption–desorption sites and thus the higher sensitivity. The \( \text{H}_2\text{S} \) sensing mechanism is based on the change in resistance of indium oxide film, which is controlled by \( \text{H}_2\text{S} \) vapor species on the surface. The energy released during decomposition of adsorbed \( \text{H}_2\text{S} \) molecules would be sufficient for electrons to jump up into the conduction band of indium oxide. An increase in operating temperature surely increases the thermal energy so as to stimulate the oxidation of \( \text{H}_2\text{S} \). The reducing gas donates electrons to indium oxide, which results in an increase in the electron concentration of the film. As a consequence, change in the resistance of indium oxide film is observed. This is the reason why the gas response increases with operating temperature.

In general, the sensitivity increases as the concentration of a test gas increases. The responses of the Indium oxide films formed at different temperatures are shown as a function of the gas concentration in Fig.4.16, respectively. As can be seen from the figure, it is obvious that the film heat treated at 350°C is quite sensitive to \( \text{H}_2\text{S} \). The improved selectivity is possibly explained as follows. When \( \text{O}_2 \), is adsorbed on the \( \text{In}_2\text{O}_3 \) surface, it traps electron(s) from the body of the n-type semiconductive \( \text{In}_2\text{O}_3 \) due to the strong
Fig. 4.16 Sensitivity of In$_2$O$_3$ films formed at different temperatures (a) 350°C (b) 450°C (c) 500°C exposed to different concentrations of H$_2$S gas.
electronegativity of the oxygen atom to produce negatively charged chemisorbed oxygen such as $O_{2}^{-}$, $O^{-}$, $O^{2-}$. As a result, the concentration of electrons in the n-type In$_2$O$_3$ decreases and hence the resistance of the material increases.

$$O_2 + e \rightarrow O_2^{-} (ads)$$

When exposed to a reducing gas, the interaction with the surface chemisorbed oxygen can take place in different ways of surface reactions. For example:

$$H_2S + (3/2) O_2 (ad) \rightarrow H_2O (g) + SO_2 (g) + (3/2) e$$

As can be seen, the electrons released return into the surface of the oxide and the resistance of the material decreases. From the point of the catalytic chemistry, the surface acid–base properties of an oxide could be advantageously utilized to favor a particular reaction on the surface. It is possible that a rare earth oxide provides the basic surface for In$_2$O$_3$ and makes it easily adsorb acidic H$_2$S gas. The response and recovery times are used to characterize the sensor performance. The response time is defined as the period in which the sensor output change reaches 90% of the steady value. The recovery time is the time for the resistance to recover 90% of the total variation when the testing gas is removed. The response times were 10s, 12s, 13s and 26s for the films heat treated at 350°C, 400°C, 450°C and 500°C respectively. As shown in the Fig.4.17, the responses to H$_2$S at 115°C is very fast, where as the recovery times are 34s, 74s, 78s and 91 s, respectively, for the films formed at 350°C, 400°C, 450°C and 500°C indicating that the films heat treated at 350°C has a
Fig. 4.17 Response and recovery times of In$_2$O$_3$ films formed at different temperatures (a) 350°C (b) 400°C (c) 450°C (d) 500°C at an operating temperature of 115°C
remarkable improved recovery characteristics. After a long time, they recovered the original state, as can be proved from the following stability test. Stability is the consistency of the sensitivity of a sensing element under continuous testing. The response of the three sensors to 10 ppm H$_2$S were measured at 2$^{nd}$, 5$^{th}$, 7$^{th}$, 12$^{th}$, 17$^{th}$, 25$^{th}$, 35$^{th}$, 50$^{th}$ days after the first measurement. It was observed that all the sensors have the nearly constant responses to 10 ppm H$_2$S, indicating good stability of the sensors.