We would like to introduce our novel indium oxide based transparent conducting oxide (TCO). Novel TCO film showed lower resistivity by lower process temperature, $197 \, \mu \Omega \cdot \text{cm}$ at $150^\circ \text{C}$, $217 \, \mu \Omega \cdot \text{cm}$ at $100^\circ \text{C}$ respectively. It can be applied to flexible touch screen (TS) favorably. This development accelerates the investigation of flexible device, which enable to access to internet easily. Our development will contribute the saving energy on the point of reduce a process temperature.

1. INTRODUCTION

In$_2$O$_3$ based transparent conductive oxide film has been widely applied to electronic devices, flat panel display (FPD), some kinds of photovoltaic devices, and touch screens. Tin doped In$_2$O$_3$ (ITO) is well known as most acceptable TCO with high conductivity, transparency and stability. ITO exhibits a low resistivity when it deposited on glass substrates with over $200^\circ \text{C}$ process temperature.\textsuperscript{[1][2]}

Recently, flexible devices have become attractive from the viewpoint of thinner, light weight. Conventional flexible device is manufactured on polymer material substrate. Hence, TCO is deposited on flexible polymer substrate instead of glass. Therefore, process temperature has to be suppressed less than glass transition temperature.

Focused on a flexible touch screen, the requirement of resistivity is less than $250 \, \mu \Omega \cdot \text{cm}$ by less than $150^\circ \text{C}$ (the average of process temperature of PET, PEN $= 130^\circ \text{C} \sim 170^\circ \text{C}$)\textsuperscript{[3]}. The film thickness is restricted under $50\text{nm}$ not to confirm visually. These properties are hard to achieve by ITO.

In this work, we successfully developed novel In$_2$O$_3$ based TCO fulfilled the above-mentioned requirement. We would like to introduce novel TCO film properties and their sputtering target.

2. EXPERIMENTAL

2.1 Preparation of sintered body and sputtering target

Our novel TCO (named USR) consists of In$_2$O$_3$ and
the other additives. USR sintered body was prepared by simply resistance heating method reported elsewhere \cite{4,5}. Commercial powder of In\textsubscript{2}O\textsubscript{3} and the other additives (the purity was over 99.9\%) were used as starting materials. After the sintering, the obtained sintered body has more than 99\% relative density. A USR sputtering target was fabricated from this sintered body by grinding and cutting.

2.2 Deposition of USR film

The USR film was deposited on a substrate by DC magnetron sputtering. The sputtering conditions are shown in Table 1.

After deposition, the film samples were annealed at 150°C in a lamp anneal furnace for 60 min with heating rate of 50°C /min under ambient atmosphere.

The measurement of film properties was investigated by following methods. Electrical properties were measured by van der Paw’s method to analyze between career density and mobility. Transmission and reflection spectra of visible wavelength region were measured by spectrometer. The micro crystal structure of film was observed by electron back scattering diffraction (EBSD) method.

### 3. RESULTS AND DISCUSSION

3.1 Electrical property

Fig.1 shows temperature dependence of electrical resistivity of USR and ITO (In\textsubscript{2}O\textsubscript{3}: SnO\textsubscript{2} = 97: 3 wt\%). USR film resistivity of 217 μΩ·cm can be achieved even at 100°C. Notably, USR film showed almost same resistivity between 100°C and 150°C. This result indicates annealing temperature can be suppressed at 100°C. Therefore, many kinds of polymer materials can be used as USR’s substrate. USR film is considered as suitable TCO materials for flexible device.

The detail of an electrical property of USR film after 150°C post annealing showed 197 μΩ·cm (Table 2). This resistivity is significant lower value compared with ITO. Especially, a career mobility of USR exhibit 1.4 times higher value than that of ITO. This relation was sustained when the mass of Sn was adjust to that of USR additives (data is not shown).

For a better understanding the electrical property of USR film, EBSD measurement was carried out to analyze the micro crystal structure of polycrystalline films. Fig.2 shows EBSD image of USR and ITO. Although almost all region of polycrystalline films consist of typical cubic (bixbyite) structure, further observation revealed that trigonal (corundum) type In\textsubscript{2}O\textsubscript{3} exists at grain boundary (Both crystal structures can be seen in Fig.3). According to EBSD quantitative analysis of corundum phase, the sum of corundum area of USR is about 5 times larger than that of ITO.

Corundum phase In\textsubscript{2}O\textsubscript{3} is known as In\textsubscript{2}O\textsubscript{3} polymorph transition from bixbyite phase at high pressure and high temperature \cite{6,7}. Karazhanov et al. reported first principle calculation and band structure analysis of bixbyite and corundum phase In\textsubscript{2}O\textsubscript{3}. Their analysis indicated that calculated effective masses for bixbyite phase are considerable larger than those for corundum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back ground pressure (Pa)</td>
<td>8.5 × 10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Sputtering gas</td>
<td>Ar</td>
</tr>
<tr>
<td>O\textsubscript{2} partial pressure (%)</td>
<td>0.5</td>
</tr>
<tr>
<td>Power (W/cm\textsuperscript{2})</td>
<td>4.5</td>
</tr>
<tr>
<td>Pressure (Pa)</td>
<td>0.7</td>
</tr>
<tr>
<td>Temperature</td>
<td>Room temperature (without any heating)</td>
</tr>
<tr>
<td>Film thickness (nm)</td>
<td>30</td>
</tr>
</tbody>
</table>

### Table 2 Electrical properties of USR film (annealing temperature : 150°C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>USR</th>
<th>ITO (SnO\textsubscript{2}:3wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (μΩ·cm)</td>
<td>197</td>
<td>331</td>
</tr>
<tr>
<td>Sheet resistance (Ω/□)</td>
<td>64.0</td>
<td>108</td>
</tr>
<tr>
<td>Mobility (cm\textsuperscript{2}/Vs)</td>
<td>51.0</td>
<td>37.1</td>
</tr>
<tr>
<td>Career density (-/cm\textsuperscript{3})</td>
<td>6.04 × 10\textsuperscript{20}</td>
<td>5.7 × 10\textsuperscript{20}</td>
</tr>
<tr>
<td>Film thickness (nm)</td>
<td>31.2</td>
<td>30.6</td>
</tr>
</tbody>
</table>
Phase [8]. Band structures of bixbyite and corundum In2O3 are shown in Fig.4. The calculations were performed with VASP package[9]. The cut-off energy was set to 500nm. Structural optimization has been performed with PBEGGA[10] on a G centered 9 × 9 × 9 k grid for corundum phase and 3 × 3 × 3 k grid for bixbyite phase respectively. After optimization, band structure was calculated with hybrid function HSE06[11] with AEXX =0.38 and AGGAX=0.62. Fermi level was set to zero. Our results support ref [8]. The conducting band minimum of corundum phase is more dispersive than that of bixbyite phase. The smallest effective masses were calculated as 0.12 for corundum phase( Γ → Z) and 0.18 for bixbyite phase( Γ → N) respectively. These results mean a career mobility of corundum phase is expected to be higher than that of bixbyite phase. Hence corundum phase of USR film may contribute the enhancement of career mobility.

3.2 Optical property

Optical property of USR film was also studied. TCO for touch screen is required high transparency at visible wavelength region. Fig.5 shows transmission spectra of USR and ITO deposited on glass substrate. Dotted line is the spectrum of glass substrate. Although transparency of USR film was almost same as ITO, there is a difference around 300 〜 400nm region. USR film showed a slightly higher transmittance even in 30nm thickness. This region is considered as band absorption. Thus it is assumed this difference is caused by Burstein-Moss effect. As considered Table.2, a career density supports this assumption.

Fig.6 shows reflectance spectra of USR and ITO respectively. Both of them showed similar spectra at visible wavelength. Therefore, similar anti-reflective coating layer can be applied to fabricate a device.
3.3 Stability

For practical application of USR film, the stability of electrical property was investigated. The accelerated degradation test with conditions of 85℃, 85% relative humidity for 1000 hour was carried out. The result is seen in Fig.7. Y axis means the relative ratio of electrical resistivity between before and after degradation. The relative ratio after 1000 hour was almost same value between USR and ITO. This result indicates USR film has good enough stability as ITO film has so that ITO can be substituted for USR.

4. Conclusion

In summary, we developed novel In\textsubscript{2}O\textsubscript{3} based TCO “USR”. The sintered body of USR can be synthesized ordinary sintering scheme and fabricated a sputtering target. The film deposition was carried out room temperature and then annealed under ambient atmosphere. A high annealing temperature was not necessary, 197 \(\mu\Omega\cdot\text{cm}\) can be achieved at 150℃ and 217 \(\mu\Omega\cdot\text{cm}\) can be achieved at 100℃ respectively. USR film has large number of corundum phase In\textsubscript{2}O\textsubscript{3} at crystal grain boundary compared with ITO film. These crystals were considered that they contribute the improvement of electrical property. Optical property and stability was almost same as ITO. These aspects allow us to treat them as if it is ITO.

REFERENCES