Supporting Information for

Mg$_x$Zn$_{1-x}$O/Ag/Mg$_x$Zn$_{1-x}$O multilayers as high performance transparent conductive electrodes

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We calculated the Mg composition of as-grown $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ films. Figure S1 shows the transmittance spectra and optical band gap of 100 nm-thick $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ films as a function of RF power ratio ($\text{Mg}_{0.2}\text{Zn}_{0.8}\text{O}/\text{ZnO}$) between ZnO target and ZnO target mixed with 20 wt.% of MgO. As RF power ratio is increased, the transmittance of $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ is increased in UV and visible wavelength region as shown in Figure S1 (a). The optical bandgap of $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ is increased from 3.24 eV at RF power ratio = 0 to 3.8 eV at RF power ratio = 1.8 as shown in Figure S1 (b). The Mg composition in $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ films with hexagonal structure was calculated by using the following equation:\textsuperscript{S1,S2}

$$E_g(\text{Mg}_x\text{Zn}_{1-x}\text{O}) = 3.24 + 2.00x \text{ (for hexagonal structure)}$$

Table S1 shows Mg compositions and optical band gaps of $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ films deposited at different RF power ratio.

**Figure S1.** (a) Transmittance spectra and (b) optical band gap of $\text{Mg}_x\text{Zn}_{1-x}\text{O}$ (100 nm) films deposited at different RF power ratio.
<table>
<thead>
<tr>
<th>RF power ratio</th>
<th>0</th>
<th>0.55</th>
<th>1.1</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical band gap (eV)</td>
<td>3.24</td>
<td>3.4</td>
<td>3.62</td>
<td>3.8</td>
</tr>
<tr>
<td>Mg composition</td>
<td>0</td>
<td>0.08</td>
<td>0.19</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Table S1.** Optical band gaps and Mg compositions of Mg$_x$Zn$_{1-x}$O (100 nm) at different RF power ratio.

We measured XRD pattern of as-grown Mg$_x$Zn$_{1-x}$O to confirm the crystal structure of Mg$_x$Zn$_{1-x}$O films as shown in Figure S2. ZnO (002) peak appears in all Mg$_x$Zn$_{1-x}$O samples, indicating Mg$_x$Zn$_{1-x}$O has a hexagonal structure.

![XRD pattern of Mg$_x$Zn$_{1-x}$O](image)

**Figure S2.** XRD pattern of as-grown Mg$_x$Zn$_{1-x}$O (100 nm) with different Mg compositions.

Figure S3 shows XRD pattern for the ZnO/Ag/ZnO and Mg$_{0.28}$Zn$_{0.72}$O/Ag/Mg$_{0.28}$Zn$_{0.72}$O on the glass substrate. Diffraction peak of Ag (111) and ZnO (002) appears in all the multilayer structure and the diffraction peak of ZnO (002) indicates that Mg$_x$Zn$_{1-x}$O has a wurtzite structure. The ZnO (002) peak of Mg$_{0.28}$Zn$_{0.72}$O/Ag/Mg$_{0.28}$Zn$_{0.72}$O is broader than ZnO/Ag/ZnO and this
peak shifts from 34.09° to 34.21° because of the strain and defect induced by Mg$^{2+}$ ions substitution.$^{53}$

![Image of XRD pattern](image)

**Figure S3.** XRD pattern of ZnO/Ag/ZnO and Mg$_{0.28}$Zn$_{0.72}$O/Ag/Mg$_{0.28}$Zn$_{0.72}$O.

Figure S4 shows optical transmittance of Mg$_{0.28}$Zn$_{0.72}$O (50 nm)/Ag (14 nm)/Mg$_{0.28}$Zn$_{0.72}$O (50 nm) with and without ion beam pretreatment on Mg$_{0.28}$Zn$_{0.72}$O bottom layer. Optical transmittance of continuous Ag film without Ag nanoparticles in Mg$_{0.28}$Zn$_{0.72}$O/Ag/Mg$_{0.28}$Zn$_{0.72}$O has low transmittance in the visible wavelength region. However, optical transmittance is improved when the continuous Ag layer with Ag nanoparticles is deposited by Mg$_{0.28}$Zn$_{0.72}$O. A continuous and smooth Ag film is not coupled with incident light, but an Ag layer with Ag nanoparticles on the surface can be coupled with light and then coupled out into air by Bragg scattering. This result was observed in all multilayer samples regardless of Mg composition as shown in Table S2.
Figure S4. Optical transmittance of Mg$_{0.28}$Zn$_{0.72}$O (50 nm)/Ag (14 nm)/Mg$_{0.28}$Zn$_{0.72}$O (50 nm) with and without ion beam pretreatment on Mg$_{0.28}$Zn$_{0.72}$O bottom layer.

<table>
<thead>
<tr>
<th>Mg composition</th>
<th>0</th>
<th>0.08</th>
<th>0.19</th>
<th>0.28</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (%) of Mg$<em>x$Zn$</em>{1-x}$O (550 nm)</td>
<td>84.5</td>
<td>84.2</td>
<td>86.5</td>
<td>87.4</td>
</tr>
<tr>
<td>$T_{AV}$ (%) of Mg$<em>x$Zn$</em>{1-x}$O (350–780 nm)</td>
<td>82</td>
<td>83.7</td>
<td>86.5</td>
<td>87.4</td>
</tr>
<tr>
<td>T (%) of Mg$<em>x$Zn$</em>{1-x}$O/Ag/Mg$<em>x$Zn$</em>{1-x}$O (550 nm)</td>
<td>93.8</td>
<td>95.3</td>
<td>94.8</td>
<td>94.2</td>
</tr>
<tr>
<td>$T_{AV}$ (%) of Mg$<em>x$Zn$</em>{1-x}$O/Ag/Mg$<em>x$Zn$</em>{1-x}$O (350–780 nm)</td>
<td>84.6</td>
<td>87.4</td>
<td>88.7</td>
<td>89.2</td>
</tr>
</tbody>
</table>

Table S2. Optical transmittance at 550 nm and average transmittance of Mg$_x$Zn$_{1-x}$O (100 nm) and Mg$_x$Zn$_{1-x}$O (50 nm)/Ag (14 nm)/Mg$_x$Zn$_{1-x}$O (50 nm) with different Mg compositions.
Reference

