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Ultrathin transparent Copper(I) oxide films grown by plasma-enhanced atomic layer deposition for Back-end-of-line p-Type transistors

Hagyoul Bae1,2,*, Adam Charnas1,2, Wonil Chung1,2, Mengwei Si1,2, Xiao Lyu1,2, Xing Sun1, Joon Park1, Haiyan Wang2, Dmitry Zemlyanov1,2 and Peide Ye1,2,*
1 Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, United States of America
2 Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, United States of America
* Authors to whom any correspondence should be addressed.
E-mail: hagyoulbae@gmail.com and yep@purdue.edu

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Abstract
We demonstrate p-type thin-film transistors (TFTs) on copper(I) oxide (Cu2O) grown by plasma-enhanced atomic layer deposition (PEALD) with bis(N,N′-di-sec-butylacetamidino)dicopper(I) as the Cu precursor and oxygen (O2) plasma as an oxidant. PEALD provides many if the advantages of other ALD processes, including uniformity and conformality, but with the additional ability to actively generate reactants and to add substantial energy from the plasma which may be important in defect control, low-temperature deposition. In this letter, Cu2O films were grown on SiO2/Si substrates under different substrate temperatures (160 ~ 240 °C) and post-deposition annealing was carried out under various temperatures (300 ~ 1100 °C) to improve the growth rate and crystallinity of the Cu2O films. The fabricated p-channel bottom-gate Cu2O transistors with a controlled thickness of 12 nm have high transparency over 90% and exhibit a subgap density of states (g(E)) of 7.2 × 1018 eV−1·cm−3 near the valence band (EV), contact resistivity (Rc) of 14 kΩ·mm, Ion/Ioff ratio of 2 × 103, and field-effect mobility of 0.1 cm2/V·s.

1. Introduction
Cu2O is regarded as one of the most promising materials for achieving p-type transition metal oxide (TMO) thin-film transistors (TFTs) [1–4]. Furthermore, to enable monolithic three-dimensional (3D) integration of high performance logic, high mobility n-type and p-type oxide semiconductor thin films that can be utilized for fabrication of back-end-of-line (BEOL) compatible complementary metal oxide semiconductor (CMOS) circuits are strongly demanded [5–8]. Cu2O is natively p-type owing to the presence of Cu vacancies, which introduce an acceptor level near valence band edge EV [9]. Cu2O itself has a cubic structure with a direct bandgap of 2.1 ~ 2.5 eV [10]. Cu2O films can formed by a variety of methods such as sputtering [11–13], spray coating [14], solution process [15], pulsed laser deposition [16], chemical vapor deposition [17], and thermal oxidation [18]. Among these deposition techniques, atomic layer deposition (ALD) is particularly suitable for oxide thin-film growth due to its conformal step coverage and accurate thickness control [19]. Although ALD-based Cu2O studies have been extensively reported [20–24], the fabrication and performance of PEALD-based Cu2O TFTs has not been demonstrated to date.

Above all, an oxygen plasma or ozone process can play an important role in the improvement of chemical reactivity and film growth rate, which is the limitation for ALD of Cu2O [25].

In this work, we present p-type TFTs fabricated on Cu2O ultrathin films grown by PEALD process for the first time. We characterized device electrical performance including Rc, g(E), and μFE as well as material properties such as phase composition, energy bandgap, and transmittance of the fabricated Cu2O TFTs, although the quality of the materials and device fabrication process need to be further improved.

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2. Experiment

Figure 1 (a) shows the key fabrication steps for the bottom-gate p-type Cu$_2$O TFTs on SiO$_2$/Si substrates using the newly developed PEALD process. The Cu$_2$O channel material was deposited by PEALD on SiO$_2$ (90 nm) on p$+$ Si wafer, which functioned as a bottom-gate. In this study, we used bis(N,N'-di-sec-butylacetamidinato)dicopper(I) as the Cu precursor and O$_2$ plasma as an oxidant. (c) A schematic diagram of the PEALD deposition cycle of Cu$_2$O film with bis(N,N'-di-sec-butylacetamidinato)dicopper(I) as the Cu precursor and O$_2$ plasma as an oxidant. (d) STEM and the corresponding EDS images of the ultrathin Cu$_2$O film on the SiO$_2$/Si substrate and schematic image of the fabricated device.

Figure 2. (a) The growth rate per cycle of Cu$_2$O film by PEALD with (a) substrate temperature (inset: image of as-dep Cu$_2$O film) and (b) deposition cycles (inset: image of transparent ultrathin Cu$_2$O film on glass substrate). (c) Cu 2p3/2 and Cu 2p1/2 peaks for the deposited Cu$_2$O film at various substrate temperatures. (d) The measured absorption spectra and optical bandgap (inset).

The Cu precursor with the solid phase was...
supplied by STREM, a company that produces a variety of high quality precursors for ALD process. As shown in figure 1(b), the optimized process consists of a Cu-precursor pulse for 20 ms with a 10 sccm N₂ flow, a purge pulse of 10 s with 100 sccm of N₂ flow, an O₂ plasma pulse for 5 s with 10 sccm under a plasma power of 300 W, and a purge pulse of 20 s with both 70 sccm of N₂ flow in main chamber and 100 sccm of N₂ flow in the plasma gas line. Next, rapid thermal annealing (RTA) at 800 °C was carried out under N₂ atmosphere for 5 min.

To define the Cu₂O channel region, we carried out mesa isolation using a BCl₃/Ar gas mixture in an inductively coupled plasma-reactive ion etching (ICP-RIE) system (Panasonic E620 Etcher) for 5 min. The etching rate of Cu₂O film is about 4 nm min⁻¹ under the process conditions used: RF power of 100 W; BCl₃ flow of 15 sccm; Ar flow of 60 sccm; pressure of 0.6 Pa. Subsequently, Ni with a thickness of 100 nm was deposited for formation of source (S) and drain (D) contacts via an electron beam evaporator. A schematic view of the p-type Cu₂O TFTs with the bottom-gate structure is shown in figure 1(c). The fabricated device has the channel width (W) of 100 μm and length (L) of 5 μm.

3. Results and discussion

To increase the deposition rate and conductivity of the atomic layer deposited (ALD) Cu₂O film, we employed PEALD process under various conditions. Figure 2(a) shows the dependence of deposition rate on deposition temperature from 160 to 240 °C. The deposition rate rapidly increases with increasing deposition temperature until 220 °C. As shown in figure 2(b), a growth per cycle (GPC) of 0.33 Å was found for a substrate temperature of 220 °C. The inset of figure 2(b) shows a PEALD-grown transparent Cu₂O film with a thickness of 12 nm on a glass substrate. Figure 2(c) shows X-ray photoelectron spectroscopy (XPS) spectra of as-deposited Cu₂O films with various deposition temperatures between 160 to 240 °C. All the samples grown between 200 to 240 °C showed the characteristic Cu 2p3/2 and Cu 2p1/2 peaks at 950.1 and 930.1 eV, respectively. Figure 2(d) shows the high measured absorption spectra of the Cu₂O film, resulting in a high transparency of approximately 90%, corresponding to an optical band gap of 2.25 eV. Figure 3 presents the gate-voltage (V_GS) dependent drain-source current (I_DS) characteristics of the fabricated bottom-gate Cu₂O TFTs after post-deposition annealing with a temperature of 800 °C, in contrast to those measured from the as-deposited films.

The measured I-V data show that the fabricated devices demonstrate clear p-channel behaviour with an increase of I_DS for negative V_GS. The I_ON/I_OFF ratio and I_DS,MAX with the as-deposited film and with various annealing temperatures are summarized in table 1. Although I_DS,MAX caused by defects and minority carriers (electrons) [26] should be improved, we note that the fabricated device with Cu₂O film annealed at 800 °C exhibits the highest I_ON/I_OFF ratio and I_DS,MAX, while the fabricated devices annealed at other temperatures have relatively poor electrical performance. It is noteworthy that high temperature annealing after film deposition gives rise to an improvement in film crystallinity and a reduction of copper vacancies in band tail states near E_V.
Figure 4. (a) Measured $I_{DS}$–$V_{GS}$ transfer characteristics at various $V_{DS}$ conditions. (b) $V_{GS}$-dependent $I_{DS}$–$V_{DS}$ output characteristics of the fabricated bottom-gate Cu$_2$O TFTs. (c) The measured C–V curves with various frequencies ($f = 0.5 \sim 10$ kHz).

Figure 5. (a) $V_{GS}$-dependent $R_{TOT}(V_{GS})$ and extrapolated $R_C$. (b) Energy distribution of extracted subgap DOS ($g(E)$) near $E_V$.

Table 1. Device parameters with various post-deposition annealing temperatures.

<table>
<thead>
<tr>
<th>@$V_{DS} = -20$ V</th>
<th>$I_{ON}/I_{OFF}$</th>
<th>$I_{DS,\text{MAX}}$ [μA μm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-dep</td>
<td>—</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>700°C</td>
<td>$\sim 9 \times 10^1$</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td>800°C</td>
<td>$\sim 2 \times 10^3$</td>
<td>$6 \times 10^{-2}$</td>
</tr>
<tr>
<td>900°C</td>
<td>$\sim 5 \times 10^3$</td>
<td>$4 \times 10^{-2}$</td>
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</table>
The measured $I_{DS}-V_{GS}$ transfer and $I_{DS}-V_{DS}$ output characteristics of the fabricated bottom-gate Cu$_2$O TFTs are shown in figures 4(a) and (b), respectively.

Furthermore, the capacitance between the gate and the short circuited S/D in the p-channel Cu$_2$O TFT under the accumulation mode was characterized using an Agilent E4980A precision LCR meter. The frequency dependent capacitance-voltage (C-V) characteristics over the frequency range from 500 Hz to 10 kHz for the gate-to-source/drain configuration are shown in figure 4(c). Also, the measured capacitance value increases as $V_{GS}$ increases in the negative direction. The results show the clear evidence for hole accumulation in the Cu$_2$O film ($V_{GS} < 0$). Especially, large frequency dispersion is attributed to capture-emission events occurring in both oxide bulk and interface with a contribution of large contact resistance ($R_C$) in S/D regions.

The $R_C$ is obtained from extrapolated $V_{GS}$-dependent total series resistance ($R_{TOT}(V_{GS})$) as presented in figure 5(a). In the fabricated p-type Cu$_2$O TFTs, a quantitative analysis of the $g(E)$ over the bandgap is a significant issue when estimating the device instability which can be affected by film quality [27]. As shown in figure 5(b), we obtained $g(E)$ of $7.2 \times 10^{18}$ eV$^{-1}$ cm$^{-5}$ over the subgap energy ranges using $V_{GS}$-dependent ideality factor obtained from the subthreshold region of the measured $I_{DS}-V_{GS}$ curve [28]. Although we successfully demonstrated the fabrication and performance of PEALD Cu$_2$O TFTs, there still remain challenges in achieving higher mobility, better switching behaviors, and lower $R_C$ in ultrathin p-type Cu$_2$O films. These issues are generally observed in the reported work related to p-type oxide transistors [11–16, 22]. More comprehensive study in particularly related to film growth and further device development are still under way.

4. Conclusion

In this work, we have developed a PEALD process to produce p-type Cu$_2$O films and demonstrated bottom-gate TFTs. P-type Cu$_2$O films are an important material building block for TMO-based BEOL transistors and circuits. The deposited Cu$_2$O thin-films with 12 nm thickness exhibited a high transparency of approximately 90%. Through post-deposition annealing at a temperature of 800 °C, the Cu$_2$O TFTs have a lower OFF-state current and a larger $I_{DS}/I_{OFF}$ current ratio of $2 \times 10^3$. These ultrathin and transparent Cu$_2$O TFTs fabricated with PEALD process could be a promising candidate for key devices for BEOL transistors in the hyper-scaled transistor era.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Hagyoul Bae @ https://orcid.org/0000-0002-2462-4198
Haiyan Wang @ https://orcid.org/0000-0002-7397-1209
Dmitry Zemlyanov @ https://orcid.org/0000-0002-1221-9195

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