Breaking the trade-off between mobility and carrier concentration in oxide semiconductors

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Abstract: Indium oxide (In_2O_3) stands out as a highly promising material for next-generation electronics due to their high electron mobility and excellent optical properties. However, the challenge lies in managing the degenerate high carrier concentration of In_2O_3. Although scaling the channel thickness can result in a reduction of the carrier concentration, this approach also leads to a degradation in mobility, results in a "trade-off" between mobility and carrier concentration, restricted its applicability in future electronic devices. This study presents a mild CF_4 plasma doping technique that effectively reduces carrier concentration in 10 nm In_2O_3. The low-temperature and low-power characteristics of remote CF_4 plasma allow fluorinated radicals to gently adsorb on the In_2O_3 surface, extracting electrons and forming stable fluorinated ions through a charge transfer mechanism, thereby achieving a pronounced counter-n-doping effect. By combining this strong counter-n-doping approach with low channel resistance characteristic in thicker In_2O_3 (10 nm), we achieve high mobility of 104 cm² V⁻¹ s⁻¹ with an excellent switching properties (I_{on}/I_{off} ratio > 10^8). This technique not only addresses the fundamental limitation of this material system but also provides a wide carrier concentration tuning window, making it suitable for monolithic 3D integration

Keywords: Amorphous oxide semiconductors, In_2O_3, high mobility, monolithic 3D integration, electron degeneracy suppression.

1. Introduction

Amorphous oxide semiconductors (AOS) have gained attention for their high electron mobility and optical properties, driving advancements in display technologies. In_2O_3 is one of the most promising material in oxide semiconductors due to its high mobility, high on current and low contact resistance. However, the excessively high carrier concentration in In_2O_3 leads to poor switching properties in the fabricated devices, which is a fundamental limitation of this material system. Recent studies have demonstrated that scaling the channel thickness down to several nanometers can reduce the carrier concentration in In_2O_3, allowing channel to turn off due to quantum confinement effects. However, as the channel thickness is reduced, mobility also degrades because of increased channel resistance and enhanced surface scattering, resulting in a trade-off between mobility and carrier concentration in In_2O_3.

To address this trade-off, it is essential to develop an effective doping approach that can reduce carrier concentration while preserving mobility. Unlike traditional bulk semiconductors, the carrier concentration in dimension-scaled materials—such as 2D materials, nanowires, and carbon nanotubes—is significantly influenced by surface effects, including adatoms and surface defects. Fluorine, with its similar atomic radius and higher electronegativity compared to oxygen, has been widely used to enhance the electrical performance of indium-based oxide semiconductors through various methods. In this study, we developed an efficient counter-n-doping technique to modulate the carrier concentration in In_2O_3, transitioning it from a near-degenerate to an intrinsic state using mild CF_4 plasma at a low temperature of 70°C and a low plasma power of 15 W. The low temperature enables fluorinated radicals to adsorb onto the surface rather than desorb immediately. Once adsorbed, these fluorinated radicals tend to extract electrons from the channel, forming stable fluorinated ions through a charge transfer mechanism. Additionally, the low-power plasma is applied remotely, filtering out a significant portion of ions, thereby minimizing ion bombardment and enabling gentle modulation of the surface properties of atomically thin In_2O_3.This modified CF_4 plasma effectively suppresses the high electron density in 10 nm thick In_2O_3, enabling switching behavior that was previously unattainable due to its degeneracy. Remarkably, the treated In_2O_3 exhibits a high mobility of 104 cm²/V·s along with an I_{on}/I_{off} ratio greater than 10^8, breaking the traditional trade-off between mobility and carrier concentration. Besides, this mild CF_4 plasma treatment also provides a wide range V_T and carrier concentration tuning window, showing its strong counter-n-doping capability.

2. Technical Work

Figure 1 a-b illustrate the I_{on}/I_{off} ratio and μ_{FE} for In_2O_3 transistors with different channel thicknesses, where Figure 2a shows the results for as-made In_2O_3 transistors and Figure 2b shows the results for In_2O_3 transistors with CF_4 plasma doping. The orange shade region in Figure 2a represents the I_{on}/I_{off} ratio for as-made In_2O_3 transistors. As previously mentioned, In_2O_3 loses its switching properties when the channel thickness exceeds 4 nm. However, after CF_4 plasma doping, In_2O_3, regardless of thickness, shows an excellent I_{on}/I_{off} ratio greater than 10^8, as indicated by the green shade region in Figure 2b. Additionally, μ_{FE} increases with channel thickness, with a maximum μ_{FE} of 104 $cm^2 V^{-1} s^{-1}$ for 10 nm In_2O_3, as shown by the grey dashed line. This indicates that the 10 nm In_2O_3 transistor achieves both high mobility (104 $cm^2 V^{-1} s^{-1}$) and an excellent switching property ($I_{on}/I_{off} > 10^8$), effectively overcoming the trade-off between mobility and the I_{on}/I_{off} ratio.

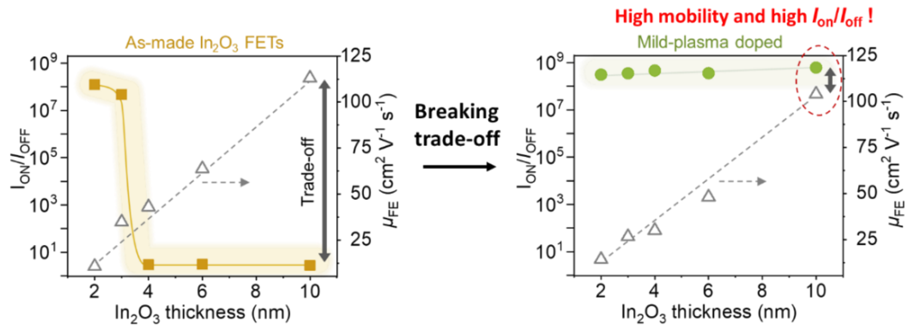

Fig. 1. I_{on}/I_{off} ratio and mobility for different In_2O_3 channel thicknesses for a) the as-made In_2O_3 transistors and b) after the mild CF_4 plasma doping.

The F 1s spectrum exhibits a peak around 685 eV, corresponding to the In-F bond, indicating that after CF_4 plasma doping, fluorine bonds with uncoordinated indium, contributing to the passivation of oxygen vacancies. Additionally, a peak around 680 eV is associated with adsorbed fluorine. In the O 1s spectrum, the peak near 531.5 eV is significantly reduced post-doping, suggesting that fluorinated radicals replace surface hydroxyl groups and adsorb onto the surface. Furthermore, by applying an acetone-isopropyl alcohol (IPA) cleaning process, the doping effect can be reversed, demonstrating its reversibility and further supporting the surface charge transfer mechanism.

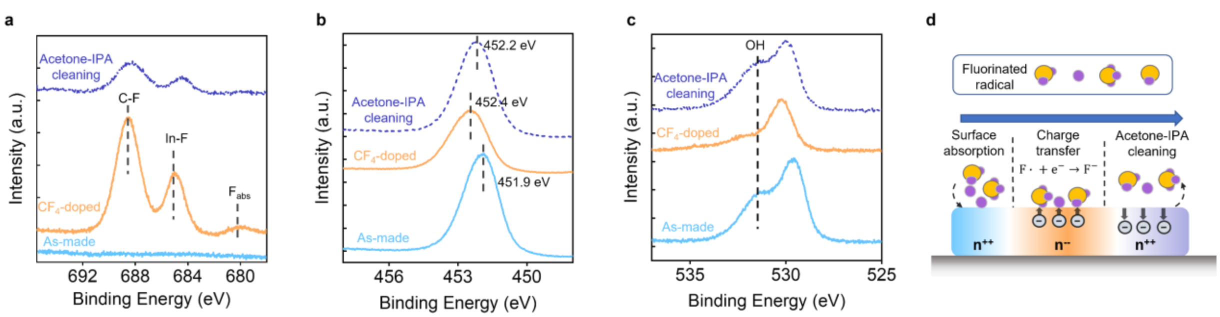

Fig. 2. XPS spectra under different conditions: as-made, CF_4-doped, and acetone-IPA cleaning for a) F 1s, b) In 3d, and c) O 1s, respectively. d) Schematic of the charge transfer mechanism of CF_4 plasma doping.

3. Conclusions

This study presents a counter-degenerate doping approach using CF_4 plasma to modulate the carrier concentration in ultrathin In_2O_3, shifting it from a degenerate to a lightly doped state and improving transistor off/on functionality. The CF_4 plasma doping process, applied post-fabrication, enables precise carrier concentration tuning and maintains optimal electrical performance. For 10 nm In_2O_3, the method achieves high mobility (104 $cm^2 V^{-1}\cdot s^{-1}$) and a high I_{on}/I_{off} ratio, effectively resolving the fundamental limitation of this material system.

References

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