# Argon Plasma-Induced Rare-metal-free Amorphous Oxide Source-Gated Transistors

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## Abstract

***Source-gated transistors using solution-processed amorphous tin (IV) oxide were developed with selective argon plasma treatment under the source region. It effectively created a Schottky contact with the ohmic metal source, eliminating the need for Schottky metals. This approach promotes advancements in low-power electronics, providing sustainable solutions for future technological applications.***

## Author Keywords

Schottky-contact controlled device; Schottky contact length; argon plasma; source-gated transistor; solution-process

## 1. Introduction

In an era of increasing demand for sustainable, energy-efficient solutions, integrating low-power electronics into Society 5.0's vision supports transformative applications in ubiquitous systems, healthcare, and agriculture. While thin-film transistors (TFTs) are the cornerstone of modern electronics, their scalability and simplicity often fall short of performance and efficiency needs in emerging applications. Source-gated transistors (SGTs) address these limitations with distinct advantages over conventional TFTs (Fig. 1 (a)): they leverage a Schottky diode (Fig. 1 (b)) to achieve rapid current saturation, enabling stable operation at lower voltages, reducing signal distortion, and enhancing performance in real-time monitoring and IoT applications [1], [2], [3].

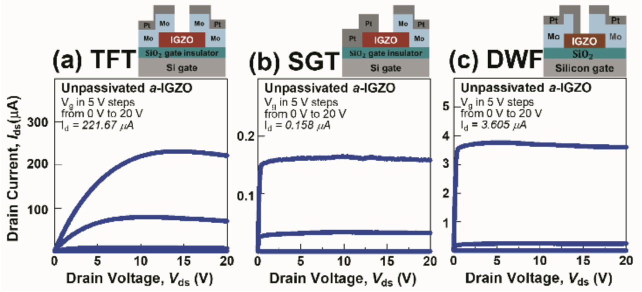

Fig. 1. (a) TFT, (b) SGT, and (c) double work function (DWF) SGT structures and their respective output characteristics [4]

Moreover, conventional TFTs often use indium-based materials, such as indium gallium zinc oxide, which pose sustainability challenges due to indium scarcity and cost. This research focuses on transitioning to tin (IV) oxide ($SnO_2$) as a channel material, offering environmental benefits, high abundance, and compatibility with solution processing for scalable fabrication. Recent work by our group introduced the DWF SGT structure, achieving higher efficiency compared to conventional SGTs (Fig. 1 (c)). However, challenges such as doping, defect control, and interfacial stability highlight the need for alternative, low-energy, and sustainable processing methods.

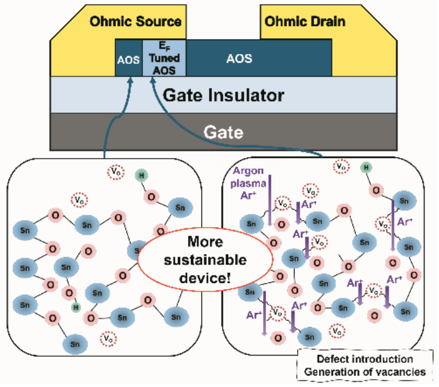

Fig. 2. Schematic of new SGT structure with tuning of semiconductor channel's Fermi energy.

Our proposed SGT design (Fig. 2) features a solution-processed channel and utilizes argon (Ar) plasma treatments to precisely tune its electronic properties [5]. Ar plasma treatment has been explored to enhance metal-oxide thin films and modulate the semiconductor's intrinsic properties [6]. By selectively modifying the Fermi energy ($E_F$) under the source contact, we establish the necessary Schottky barrier while using standard ohmic source metals. This would streamline the fabrication and improve material compatibility. The process would ensure low-power operation, distinct saturation characteristics, and even scalability. This research also introduces and integrates a custom-built low-temperature atmospheric pressure plasma (APP) for Ar plasma treatment as a sustainable alternative to vacuum plasma source systems. APP operates at ambient pressure, eliminating the energy demands of vacuum-based setups, and auxiliary equipment. This efficiency directly supports the sustainability goals of our research by minimizing the fabrication process's energy footprint.

By integrating this technology with solution-processed SGTs, this research aims to establish a scalable, and more sustainable SGT fabrication process. This approach advances the development of low-power, making the APP system a transformative tool in sustainable electronics.

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## 2. Experimental Procedure

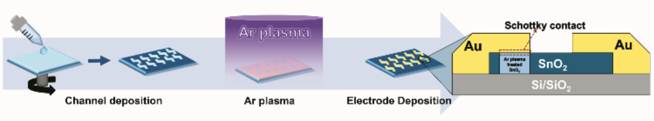

Fig. 3. Fabrication process of P-SGTs.

The fabrication flow is illustrated in Fig. 3. In this study, solution combustion synthesis (SCS) was implemented to deposit the $SnO_2$ channel layer. The addition of silver nitrate was implemented due to its effectiveness as a chloride remover which resulted in enhancement of semiconductor properties [7]. The resulting solution was spin-coated on a p-type doped silicon substrate with 105 nm silicon dioxide as the gate insulator and underwent combustion by baking for 1 h at 300 °C. Conventional photolithography was implemented to pattern the semiconductor channel. Ar plasma ignited at vacuum and atmospheric conditions were explored in this study. An inductively coupled plasma–reactive ion etching (ICP-RIE) with 300 W ICP power, 100 W bias power, 5 Pa working pressure, 50 sccm Ar flow, and 15 s exposure time were employed to activate the $SnO_2$ and form a Schottky junction near the edge under the source region. On the other hand, a custom-built APP system shown in Fig. 4 (a,b) was also fabricated in this study to induce Ar plasma in ambient conditions. Variable plasma parameters such as nozzle-to-substrate distance, operating voltage, and Ar flow rate were explored. Gold (Au) metal electrodes were then deposited onto the channel as source and drain electrodes.

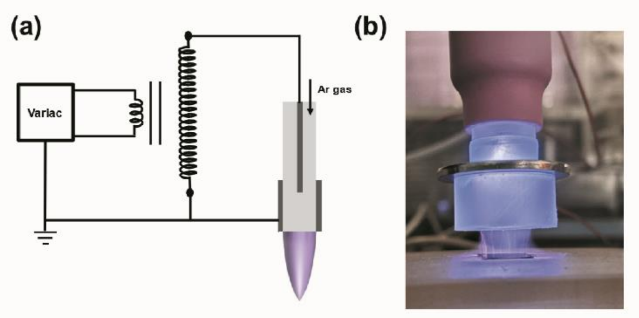

Fig. 4. (a)Schematic diagram of APP system and (b) actual image of Ar plasma treatment on $SnO_2$ films.

Output curves of fabricated P-SGTs were measured using Agilent 4156C Precision Semiconductor Parameter Analyzer. X-ray Photoelectron Spectroscopy (XPS) with a mono-Al Kα source (1486.6 eV) was used to determine the ratios of various metal-oxide (MO) bonds present before and after the Ar plasma treatment. Ellipsometry measurements were used to determine the optical band gap energy ($E_g$) of the films. Atomic force microscopy (AFM) measurements were done to evaluate the effect of Ar plasma on the surface of $SnO_2$ films. Ultraviolet photoelectron spectroscopy (UPS) measurements were used to measure the work functions of as-fabricated and Ar plasma treated $SnO_2$ films, and the Au metal contact used in this study. UPS and optical measurements were also used to create the energy band diagram of metal-semiconductor (M-S) contact and to estimate the $E_F$ based on the band gap energy ($E_g$) and valence band onset.

## 3. Results and Discussions

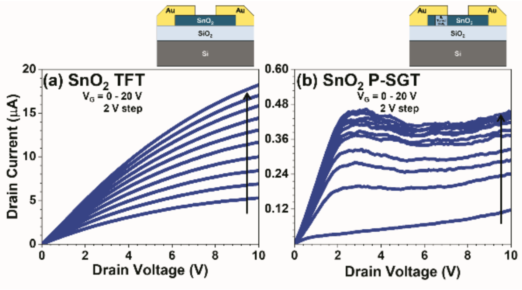

Fig. 5. Output characteristics of $SnO_2$ (a) TFT and (b) P-SGT.

The output characteristics of our fabricated plasma-induced source-gated transistors (P-SGTs) are presented in Fig. 5. In this configuration, Ar plasma was induced in a high vacuum environment through an ICP-RIE system. In comparison to the reference thin-film transistor (TFT) with zero Schottky contact length (SCL) in Fig. 5(a), the P-SGT exhibits lower drain currents, even at higher gate voltages. Also, the P-SGT device displayed abrupt current saturation, whereas the TFT with zero SCL showed more linear and conductive behavior. It is good to take note that $SnO_2$ has a high intrinsic carrier concentration [8], leading to a more linear trend, and current saturation was unattainable. To assess the effects of Ar plasma treatment on the $SnO_2$ channel, various film characterizations were performed. X-ray Diffraction (XRD) spectra in Fig. 6 showed no defined peaks corresponding to Sn-related compounds which confirm the amorphous phase (a-$SnO_2$) of the film before and after Ar plasma exposure. AFM measurements revealed a smooth topography of the semiconductor channel before and after the Ar plasma treatment at 0.50 nm and 0.70 nm of roughness, respectively. The effect of Ar ion bombardment on the a-$SnO_2$ films could be the cause of the slight increase in the surface roughness. XPS measurement revealed an increase in the non-stoichiometric bonds (M-$O_{II}$) from 16.0 % to 24.0 %. This increase can be indirectly attributed to oxygen vacancies which confirms the generation of oxygen vacancies due to Ar ion bombardment on the surface of the a-$SnO_2$ films.

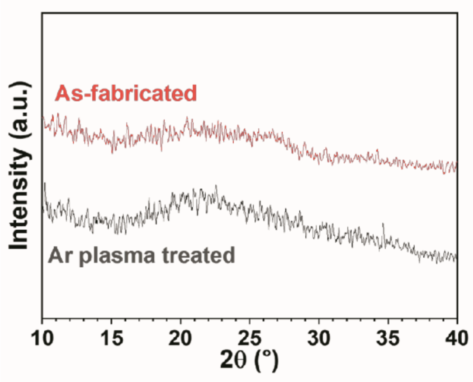

Fig. 6. XRD of a-$SnO_2$ films: as-deposited and after exposure to Ar plasma.

Optical measurements, reveal a $E_g$ reduction from 4.30 eV to 4.00 eV in the Ar plasma-treated films, indicating an increase in free carriers that enhances electrical conductivity. The energy band diagrams for as-fabricated and Ar plasma-treated a-$SnO_2$, shown in Fig. 7, were derived from UPS and $E_g$ measurements. We observe a shift in the $E_F$ closer to the conduction band which suggests a change in intrinsic properties due to oxygen vacancies and defects introduced by Ar plasma treatment. The raise in $E_F$ closer to the conduction band is likely linked to the reduced optical band gap and changes induced by the Ar plasma treatment.

Upon the Au deposition on the source region, two contacts were formed: one with the as-fabricated a-SnO$_2$ and another with Ar plasma-treated a-SnO$_2$. The measured work function of Au (5.15 eV) closely aligns with that of a-SnO$_2$ at around 5.05 eV, creating a low resistance, that facilitates efficient electron transfer. In contrast, the introduction of oxygen vacancies in the Ar plasma-treated a-SnO$_2$ decreases its work function [9], producing a mismatch with Au that generates a Schottky barrier at the treated a-SnO$_2$ interface. This mismatch results in significant band bending and a depletion region that impedes electron movement, especially when a bias is applied, forming a Schottky contact near the source edge.

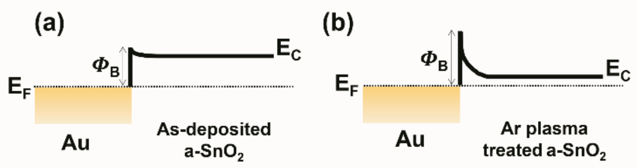

Fig. 7. Energy band diagrams of (a)Au/As-deposited a-SnO2 and (b) Au/Ar plasma treated a-SnO2.

These results highlight the crucial role of plasma treatment in modifying a-SnO$_2$ electronic properties, which are key for achieving Schottky behavior in SGTs. On the other hand, the use of APP in Ar plasma treatment would make the process highly efficient, sustainable, and suitable for scalable, roll-to-roll processing, as well as flexible electronics for low-power applications. Integrating APP into SGT fabrication is a step toward scalable, energy-efficient electronics for a sustainable future.

## 4. Conclusion

This study revealed a novel structure for producing an alternative and effective method for SGT by selectively tuning the a-SnO$_2$ channel beneath the ohmic source region through Ar plasma treatment. The resulting structure demonstrated SGT behavior with early output current-voltage saturation. Changes in the $E_F$ between the as-deposited and Ar plasma-treated films substantiated the work function modification. Notably, this innovative approach simplifies the SGT fabrication process by enabling the use of ohmic contacts for both the source and drain.

## 5. Acknowledgement

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