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Oxygen Vacancy Dynamics in a-IGZO Synaptic Transistor

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Abstract. Amorphous indium gallium zinc oxide (a-IGZO) has become one of the most important oxide semiconductor materials used in thin-film transistor and neuromorphic device research because of its high carrier mobility, optical transparency, and compatibility with low-temperature fabrication processes. In contrast to conventional amorphous semiconductors, a-IGZO can still preserve relatively strong electrical performance even without long-range crystal order. Such behavior is closely associated with the electronic structure of metal-cation s orbitals and the transport mechanism found in amorphous oxide semiconductors. At the same time, intrinsic defect states, particularly oxygen vacancies, strongly affect the electrical characteristics of the material. In conventional transistor applications, oxygen vacancies are often regarded as instability sources. However, in synaptic transistors, these same defects can contribute to useful device functions because they introduce time-dependent carrier trapping and release behavior. This paper reviews the physical role of oxygen vacancies in a-IGZO synaptic transistors, including charge transport in amorphous IGZO, defect formation, photoinduced current response, lattice relaxation, and persistent photoconductivity. Particular emphasis is placed on how oxygen-vacancy dynamics influence excitatory postsynaptic current and memory-related conductance modulation.

Keywords: Oxygen vacancies, a-IGZO, Synaptic transistors, Persistent photoconductivity

1. Introduction

In recent years, neuromorphic electronics have received considerable attention as conventional computing systems continue facing limitations in energy efficiency and data-transfer speed. In traditional computer architectures, memory and processing units are physically separated, meaning that information must repeatedly move between storage and computation during operation. This repeated transfer process increases both latency and power consumption and is commonly referred to as the von Neumann bottleneck [1].

To reduce these limitations, many researchers have investigated neuromorphic devices that imitate certain behaviors of biological neural systems. Among different device structures, synaptic transistors have become especially important because their conductance state can be affected not only by present electrical stimulation but also by previous input signals. Owing to this history-dependent behavior, synaptic transistors are capable of reproducing several basic synaptic functions, including excitatory postsynaptic current and short-term plasticity effects [1].

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Oxide semiconductors have gradually become attractive candidates for neuromorphic applications because they combine relatively simple fabrication processes with tunable electrical properties. Among these materials, amorphous indium gallium zinc oxide (a-IGZO) has been studied extensively in recent years. After Nomura et al. demonstrated transparent a-IGZO thin-film transistors fabricated at room temperature, the material quickly attracted attention in thin-film electronics research because of its high carrier mobility, optical transparency, and compatibility with low-temperature processing conditions [2].

Compared with conventional amorphous silicon, a-IGZO maintains relatively high carrier mobility while also preserving good uniformity over large-area substrates [3]. This property makes the material suitable for applications such as display backplanes and flexible electronics. Although long-range crystal order is absent in a-IGZO, efficient carrier transport can still occur because the conduction band mainly originates from spatially isotropic metal-cation s orbitals instead of directional covalent bonding [4]. This transport mechanism is considered one of the major differences between amorphous oxide semiconductors and conventional amorphous semiconductors [5].

Interest in a-IGZO later expanded beyond ordinary TFT applications. In neuromorphic devices, the electrical response is strongly affected by intrinsic defect states inside the material. Among these defects, oxygen vacancies are especially important because they influence carrier transport, threshold-voltage stability, and photo-induced conductivity behavior.

In conventional transistor studies, oxygen vacancies are often regarded as instability sources. However, in synaptic transistors, the same defects can also contribute to memory-related current modulation because carrier release and recombination do not occur immediately [6, 7]. Delayed carrier processes associated with oxygen vacancies therefore become closely related to the time-dependent electrical behavior observed in a-IGZO devices.

Earlier studies mainly focused on transistor mobility improvement, fabrication optimization, and suppression of environmental instability in a-IGZO systems. Later work began examining oxygen vacancies in relation to threshold-voltage shift and long-term electrical reliability [6, 8]. In neuromorphic applications, however, oxygen vacancies behave less like static defects and more like dynamic carrier-related centers whose behavior evolves under external stimulation. Vacancy-related carrier release, delayed recapture, and local structural relaxation can all influence transient current response and persistent conductance change inside the device [6, 9].

Although many experimental studies have demonstrated synaptic behavior in a-IGZO devices, the physical connection between oxygen-vacancy dynamics and synaptic current evolution is often discussed only briefly. As a result, the relationship between defect physics and time-dependent electrical response is sometimes difficult to follow clearly.

This paper therefore focuses on oxygen-vacancy dynamics in a-IGZO synaptic transistors and discusses how defect-related physical processes contribute to synaptic current generation. The discussion includes charge transport in amorphous IGZO, oxygen-vacancy formation, photo-induced ionization, structural relaxation, and persistent photoconductivity, with particular attention given to how these processes influence synaptic electrical behavior [4, 6, 9].

2. Basic charge transport mechanism in a-IGZO

2.1. Orbital origin of conductivity

One unusual feature of a-IGZO is that relatively high carrier mobility can still be maintained even though the material lacks long-range crystal order. This behavior is different from conventional

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amorphous semiconductors such as amorphous silicon and is closely related to the electronic structure of the oxide network [4].

The conduction band in a-IGZO mainly originates from metal-cation s orbitals. Among the three major cations in the material, indium contributes most strongly because In 5s orbitals form the dominant conduction pathway inside the amorphous structure. Zn 4s orbitals also participate in conduction, although their contribution is weaker. Gallium plays a somewhat different role. Rather than directly improving conductivity, Ga tends to suppress excessive free-electron generation through relatively strong Ga–O bonding, which helps improve electrical stability [3].

Because these s orbitals possess nearly spherical symmetry, neighboring orbitals can still overlap effectively even when the atomic arrangement becomes disordered. As a result, carrier transport in a-IGZO is less sensitive to structural disorder than in amorphous silicon, where directional covalent bonding plays a much more important role [4].

Composition balance also affects transport behavior. Indium-rich compositions generally exhibit higher mobility, while excessive gallium tends to reduce carrier concentration because oxygen-vacancy-related electron generation becomes suppressed.

2.2. Percolation conduction

Although orbital overlap allows carrier transport in amorphous IGZO, electron motion inside the material is not spatially uniform. The amorphous oxide network contains local variation in bond angle, bond length, and metal–oxygen coordination. Because of this disorder, the local conduction-band minimum fluctuates throughout the material [5].

Instead of moving uniformly across the channel, electrons preferentially travel through regions where the local conduction-band energy is lower. Connected low-energy regions therefore behave as favorable transport pathways, while higher-energy regions act more like barriers. This transport picture is commonly described as percolation conduction [5].

Under the percolation model, mobility depends strongly on the continuity of these low-energy pathways. Even relatively small local structural differences can influence transport behavior because they modify pathway connectivity and local transport barriers.

Thermal treatment also affects this process. Experimental studies showed that annealing improves mobility mainly through local structural relaxation, which reduces transport barriers and improves orbital overlap between neighboring cations [5]. Oxygen vacancies later become important because vacancy-related defects can also modify the local conduction-band landscape and therefore affect percolation transport directly.

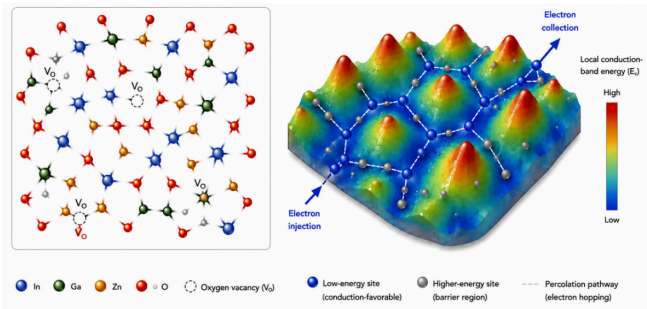

Figure 1. Schematic illustration of disorder and percolation conduction in amorphous IGZO. (a) Disordered a-IGZO network (atomic scale), (b) Energy landscape and percolation conduction pathways (meso scale)

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Figure 1 illustrates this idea schematically. In Fig. 1(a), the amorphous IGZO network contains randomly distributed metal cations and oxygen vacancies without long-range crystal order. Figure 1(b) shows how spatial fluctuation of local conduction-band energy produces connected low-energy pathways through which electrons preferentially move.

2.3. Gate bias dependence and fermi level shift

Carrier transport in a-IGZO is influenced not only by structural disorder but also by trap states distributed inside the bandgap. These trap states mainly originate from intrinsic defects and local bonding irregularities in the amorphous oxide structure.

Many of these energy levels are located below the conduction-band edge. As a result, electrons can become temporarily trapped before contributing fully to channel conduction. Early transistor studies estimated that deep trap density in a-IGZO thin-film transistors is on the order of 10^{16} cm^{-3} eV^{-1}, indicating that trap-assisted transport remains important even under normal operating conditions [8].

Trap states close to the conduction-band edge are especially important because they strongly affect threshold voltage, subthreshold swing, and the onset of channel conduction.

More recent ultrabroadband photoconduction measurements further suggested that these subgap states are not distributed as one broad defect band. Instead, several distinguishable energy peaks appear across the bandgap, including oxygen-vacancy-related donor-like states and deeper acceptor-like states [9].

During positive gate bias, electrons accumulate near the gate dielectric interface and first occupy available trap states. As the Fermi level gradually shifts toward the conduction-band minimum, more carriers participate in continuous transport and the current begins increasing. Because part of the injected charge remains trapped temporarily, current growth in the subthreshold region occurs gradually rather than abruptly.

3. Oxygen vacancy physics in a-IGZO

3.1. Formation and property of oxygen vacancy

Oxygen vacancies are commonly discussed when analyzing the electrical behavior of amorphous IGZO. Their influence appears in carrier transport, conductivity variation, and bias-dependent response characteristics.

Inside the oxide network, a vacancy forms once an oxygen atom is missing from the lattice. The missing oxygen leaves defect-related electronic states behind, and some of these states may contribute electrons to the system under suitable conditions [6]. Because of this, oxygen vacancies are usually treated as electrically active defects rather than simple structural imperfections.

The probability of vacancy formation is not identical throughout the material. Local composition plays an important role here. Gallium-rich regions generally suppress oxygen-vacancy generation because Ga–O bonds are relatively strong. Regions containing more indium behave differently and tend to allow vacancy formation more easily [6].

As a result, the spatial distribution of oxygen vacancies in amorphous IGZO is normally nonuniform. Local defect density therefore changes from region to region, which later influences transport behavior in the channel.

Electronic states introduced by oxygen vacancies may appear near the conduction-band edge or deeper inside the bandgap. Consequently, these defects can participate in both carrier transport and

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trapping processes during transistor operation.

3.2. Deep trap and donor duality

Oxygen vacancies in amorphous IGZO do not always contribute in the same way during transistor operation. Their behavior changes with local bonding condition, nearby defect environment, and external bias condition.

Some vacancy-related states are located close to the conduction-band edge. In this situation, electrons can be released relatively easily and the defect behaves more like a shallow donor [6]. Increased carrier concentration is then observed together with higher conductivity.

Different behavior appears when the defect state is located deeper inside the bandgap. Instead of supplying free carriers efficiently, these deeper states tend to trap carriers temporarily. Electrical response becomes slower under such conditions, and instability-related behavior is more likely to appear during operation.

Threshold-voltage shift and hysteresis are frequently discussed together with this trapping effect. Under NBIS conditions, oxygen vacancies may capture holes and become positively charged [10]. Charge accumulation near the interface region can then influence later transistor response.

For this reason, oxygen vacancies are difficult to classify using only one description. Depending on operating condition, the same defect may either assist carrier transport or contribute to instability-related behavior.

3.3. Metastable ionization and structural relaxation

Another characteristic often discussed in a-IGZO is metastable defect behavior under external excitation.

Once electrons leave vacancy-related states, local rearrangement may occur around nearby metal atoms [6]. The ionized configuration then becomes relatively stable. Immediate recombination is suppressed.

This behavior is closely connected with persistent photoconductivity observed experimentally in a-IGZO devices [7]. In some measurements, elevated current remains detectable even after optical excitation has already been removed.

The effect also depends on excitation condition. Weak illumination may produce only limited response, whereas stronger excitation allows metastable behavior to develop more clearly. Structural relaxation contributes additional recombination barriers, so carrier recovery becomes slower afterward.

Because both electronic transition and local atomic rearrangement are involved, the mechanism is usually discussed as more than ordinary trapping and detrapping behavior.

3.4. Implication for electrical response

Defect-related carrier dynamics strongly affect how current evolves in a-IGZO devices.

After external stimulation is introduced, current response usually develops gradually instead of appearing immediately. Similar delay can also be observed during recovery after the stimulus disappears [6].

As a result, electrical behavior at a certain moment is still influenced by earlier excitation history. This time-dependent response later becomes important in synaptic transistor studies.

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4. Dynamic response of oxygen vacancy

4.1. Time-dependent current response

In experiments on a-IGZO devices, the current usually does not respond immediately after external stimulation is applied. Instead, the electrical response changes over time under both voltage excitation and optical excitation conditions.

A typical example can be observed during light illumination. Rather than reaching a stable value instantly, the channel current keeps increasing while the light remains on. After illumination is removed, the current often stays at a relatively high level for some time before gradually decreasing. This delayed decay process is generally associated with persistent photoconductivity (PPC) [7].

Electrical measurements show a similar tendency. Longer pulse duration or stronger stimulation commonly produces a larger current response together with slower recovery behavior. Since carrier trapping and recombination processes require time to complete, the current measured at a certain moment is usually still affected by signals applied earlier.

Because of this delayed response, the electrical behavior of a-IGZO devices depends not only on the present stimulation condition but also on previous excitation history. This time-dependent characteristic later becomes important for synaptic operation in neuromorphic devices.

4.2. Relation to synaptic behavior

Several electrical characteristics observed in a-IGZO devices resemble the response behavior of biological synapses. In particular, conductance does not simply switch between two fixed states during stimulation. Instead, gradual conductance modulation can usually be observed.

Experimental studies reported that IGZO-based synaptic transistors are capable of reproducing such behavior under both electrical and optical stimulation conditions [11]. During repeated stimulation, conductance often increases progressively rather than changing only once. After the external signal disappears, recovery also occurs gradually instead of instantaneously.

Previous stimulation can therefore continue influencing later electrical response. Such history-dependent behavior is important for neuromorphic systems because temporary signal retention and conductance modulation are both required for artificial synaptic operation.

For this reason, a-IGZO has attracted attention as a potential material system for neuromorphic devices.

5. Synaptic characteristics of a-IGZO devices

5.1. Excitatory postsynaptic current

In many measurements on a-IGZO synaptic transistors, current does not disappear immediately after stimulation is removed. Instead, gradual decay behavior is usually observed for a certain period.

A transient response of this type is commonly referred to as excitatory postsynaptic current (EPSC) in neuromorphic device studies.

The behavior can be produced using either electrical pulses or optical stimulation. During excitation, channel conductance increases progressively rather than changing instantaneously. Recovery afterward is also relatively slow.

Pulse condition influences the measured response noticeably. Higher pulse amplitude or longer stimulation time generally produces stronger EPSC signals together with longer decay behavior.

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Because of this, EPSC measurement is widely used when evaluating synaptic characteristics in IGZO-based devices.

5.2. Paired-pulse facilitation

Paired-pulse facilitation (PPF) is another commonly reported characteristic in a-IGZO synaptic devices.

When the interval between two pulses is short, the second response often becomes larger than the first one. In many experiments, this enhancement effect decreases gradually as pulse spacing increases.

Incomplete recovery after the first stimulation is usually considered the main reason. Since part of the conductance enhancement still remains before the second pulse arrives, the later response starts from a relatively higher conductance state.

The phenomenon further shows that previous stimulation continues influencing later electrical behavior inside the device.

5.3. Short-term and long-term memory behavior

Retention behavior in a-IGZO devices changes under different stimulation conditions.

Under relatively weak stimulation, conductance enhancement is usually temporary. After a short period, the device gradually returns close to its initial state. This type of behavior is generally associated with short-term memory response.

Different behavior can appear during repeated stimulation. Once multiple pulses are introduced continuously, conductance recovery becomes noticeably slower and part of the conductance change may remain even after external excitation has already ended.

Experimental studies often relate this behavior to charge accumulation together with defect-related carrier processes inside the device. With repeated stimulation, the conductance state gradually becomes more stable.

Pulse width, pulse number, and stimulation intensity can all influence retention time and recovery behavior.

6. Conclusion

This paper focused on the role of oxygen vacancies in a-IGZO synaptic transistors and how this intrinsic defect affects both electrical transport and device behavior. First, the charge transport in a-IGZO was introduced. Compared with conventional amorphous semiconductors, conduction in a-IGZO is mainly determined by metal cation s orbitals and percolation pathways. This allows carriers to move effectively even in a disordered state. Then, oxygen vacancies were analyzed as key defect states with dual roles. Under different situation, they can act as both shallow donors and provide free electrons, or form deeper trap states that capture carriers and influence the electrical response of the device. Under electrical or optical stimulation, oxygen vacancies show dynamic behavior. They can release carriers and recapture them with a delay. This process is related to metastable ionization and structural relaxation, which together lead to delayed recombination and persistent photoconductivity. As a result, the current in a-IGZO devices does not respond instantaneously, but instead increases gradually during stimulation and decays slowly after the external stimulus is removed. Because of this time-dependent behavior, a-IGZO devices can exhibit synaptic characteristics similar to biological synapses. The electrical response can be associated with behaviors such as excitatory

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postsynaptic current, paired-pulse facilitation, and memory-like conductance modulation. Therefore, oxygen vacancies should not be considered only as defects that cause instability. Their dynamic behavior also plays an important role in producing the time-dependent electrical response observed in a-IGZO synaptic devices. By controlling the distribution and behavior of oxygen vacancies, it may be possible to further improve device performance and expand their potential use in neuromorphic applications.

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