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$SrTiO_3$ as an Active Photoconductive Platform: Interfacial Mechanisms, Functional Materials, and Optoelectronic Devices

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Abstract- *$SrTiO_3$ (STO) is a fantastic platform for developing photoconductivity. When combined with functional overlayers, $SrTiO_3$ has many great properties, including large band-gaps, a lot of defects and tunability, excellent charge carrier mobilities, and great interfacial physics due to the ability to support many materials. This paper will provide a comprehensive view of photoconductive responses of oxide and non oxide materials grown on $SrTiO_3$ substrates, as well as highlight how $SrTiO_3$ has an active role in the design of integrated photonics as opposed to only serving as a passive substrate. The first part of this review will highlight some of the fundamental mechanisms of photoconductivity and the mechanisms causing photoconductivity associated with defects, band bending at the interface between materials; charge transfer due to irradiation will also be discussed. After examining the mechanisms causing these responses, a detailed assessment of the various systems of materials will occur, including polar, correlated, ferroelectric, semiconducting and two (2D) dimensional materials that have been used in conjunction with $SrTiO_3$.Ferroelectrics, such as $BaTiO_3$, and $SrTiO_3$ combined together can create photoconduction in a controllable and nonvolatile manner through polarization controlled band alignment. Similarly, correlated materials such as $SrRuO_3$ and $LaNiO_3$ induce photoconductive responses due to the hot-carrier injection mechanism and being substrate-assisted. The last section of this paper will describe hetero-structures that may also substantially enhance the response and carrier lifetime of materials used for photoconduction. In this section, specific classes of materials and predominant mechanisms, spectral response wavelength range, and characteristic times applicable to the classes of materials and type of material used to fabricate the devices will be presented in a table for more valid comparisons of classes of sample materials and the device architecture. Example of the devices will include photoelectric detectors, optically toggled transistors, non-volatile electrical storage elements, and neuromorphic devices. Finally, issues related to the management of defects, stability, speed/gain trade-offs, and the scale of the research associated with using this principle will be presented to provide clarity on the future efforts of researchers employing this material. By integrating the explanations of classes of materials and the chambers of electric devices, the development of transparent heterostructures made from $SrTiO_3$ has an unlimited opportunity to build on the previously established systems and provide an effective method for developing opto-electrical or Adaptive Electrical Systems in the future.*

Key Words: Photoconductivity, Oxide Interfaces , Ferroelectrics, Thin-film, $LaAlO_3/SrTiO_3$, $BaTiO_3/SrTiO_3$, $LaNiO_3/SrTiO_3$, $SrRuO_3/SrTiO_3$ and $NdGaO_3/SrTiO_3$

1. INTRODUCTION

Photoconductivity is a key component of the modulation of material properties by light used in photodetectors, solar cells, and optical sensors. Traditional photoconductivity in semiconductors is based primarily upon band-to-band excitation and subsequent recombination of charge carriers, while photoconductivity in oxide heterostructures and oxides is very different due to a number of factors, including strong electronic correlations, structural distortions of the crystal lattice, defect states, and changes in electronic structure at the interface of oxide materials. Strontium titanate ($SrTiO_3$ or STO) is an oxide parent material that is significant to this discussion [1-2]. While STO was originally used as a mechanical substrate for the growth of various oxide materials, it is now recognized as an effective electro-optical component. Over the past 20 years, various experiments have shown that the electrical conductivity of oxide-based heterostructures utilizing STO can be reversibly controlled by the application of light, including the persistent photoconductivity (PPC) effect, which persists from hours to days at ambient conditions [3-5]. The phenomena associated with the suspected use of these devices cannot be accounted for using traditional semiconductor photoconductivity models. Instead, these characteristics are the result of the interaction of defects in the substrate with the band alignment at the interface and differences in electronegativity between the substrate and the overlayer of material at the interface. The discovery of a high-mobility 2DEG at the $LaAlO_3$ / STO interface has created a great deal of interest in the potential of STO to serve as a medium for confining mobility at the interface [6]. Subsequent measurements have shown that the application of light can have a dramatic modulating effect on interfacial conductivity further establishing the importance of STO with respect to photoconductivity [7,15,21]. A new class of materials comprising a variety of oxides, correlated metals, ferroelectrics, wide-bandgap semiconductors, and two-dimensional materials has been shown to grow on STO and exhibit substrate-mediated photoconductivity. While there are now a substantial number of experimental publications addressing photoconductivity in oxide heterostructures, to date, no review has provided a thorough, systematic overview of the various classes of materials that are grown on STO substrates. This review provides a comprehensive overview of photoconductivity in STO heterostructures, outlines the fundamental physical

principles that govern photoresponse in these materials, and identifies the key material properties that are required for rationally implementing interface and defect engineering.

2. Electronic and Optical Properties of $SrTiO_3$ Relevant to Photoconductivity

Strontium titanate ($SrTiO_3$ or STO) is a cubic perovskite oxide at ambient temperatures, with a lattice constant of approximately 3.905 Å. This makes it a good match for many types of oxide thin film materials. The electronic structure of $SrTiO_3$ indicates that the conduction band is made predominantly of Ti 3d (t2g) orbitals while the valence band consists of O 2p states [8]. When $SrTiO_3$ is properly formed with regard to stoichiometry, it has a band gap and behaves as an insulating semiconductor. However, slight variations from the ideal stoichiometric composition can result in mobile charge carriers being present in the $SrTiO_3$ material. One of the more interesting properties of $SrTiO_3$ is the very large dielectric constant, which can be greater than 300 at room temperature, and continues to increase rapidly at lower temperatures [9]. The high dielectric screening provided by $SrTiO_3$ allows for a significant reduction in Coulombic forces between electrons and holes, facilitates charge separation, and inhibits electron/hole recombination. Therefore, charge carriers that have been injected or generated in /under the $SrTiO_3$ material will have very long carrier lifetimes, which is critical for improved photoconductivity and photonic applications. defects in $SrTiO_3$ have a significant impact on photophysical properties of $SrTiO_3$. Specifically, the presence of oxygen vacancies in $SrTiO_3$ adds shallow donor levels to the electrical conductivity, resulting in the formation of localized states within the band gap that can absorb incident photons with energies less than or equal to the bandgap, (i.e., sub-bandgap absorption) [10]. When light interacts with $SrTiO_3$, the oxygen vacancies in $SrTiO_3$ will often capture photoexcited charge carriers, resulting in the creation of a meta-stable, conductive state [3,5,10]. In addition, oxygen vacancies are very mobile within $SrTiO_3$, particularly at elevated temperatures and/or while under applied electric fields, allowing for rapid change in carrier density during the formation of oxide thin films and the optically excited oxide thin films [17,20]. $SrTiO_3$ undergone a structural phase transition from cubic symmetry to tetragonal symmetry at approximately 105 K, which is characterized by changes in lattice phonons and lattice distortion [9]. The structural phase transition will also affect carrier mobilities within $SrTiO_3$ and influence defect behavior, leading to a temperature-dependent behavior in the photoconductivity of $SrTiO_3$. Collectively, the band gap, strong dielectric screening, defect sensitivity, and structural adaptability of $SrTiO_3$ make it an ideal material to exhibit novel photoconductive properties when combined with other epitaxially grown thin film materials.

3. Role of $SrTiO_3$ as an Active Substrate

Strontium titanate ($SrTiO_3$) also referred to as STO, serves not only as a mechanical substrate for oxide heterostructures, but also an additional contributing factor in terms of determining how these types of materials will behave when exposed to light (or photoconductively). Due to its property of having been able to maintain partial ferroelectric characteristics, as well as being characterized by a high ability for electrical energy storage (dielectric constant), a very large degree of suppression of electric fields induced from (dielectric screening) and its ability for providing possible source of defects (due to oxygen vacancies), STO can significantly alter many features related to strain states, interfacial band alignment and dynamics associated with photoexcited charge carriers that reside in an epitaxial material that has been deposited on top of the STO surface [1-2]. Examples include conductivity due to oxygen vacancies, long lifetimes of photoexcited charge carriers. These properties of the STO substrate, combined with how STO interacts with the oxide material that has been deposited on it (through oxygen vacancies), result in producing effects related to photoconductivity in various heterostructures that utilize STO as one of the components that make up their structure cannot adequately explain the photoconductive properties of the overall structure without first accounting for some electronic-related structure and defect-mediated response [3,5,10].One aspect of understanding how these features impact overall photoconductivity is to consider lattice-matched epitaxy growth of an oxide overlayer/superlattice on an STO substrate; interfacial band bending which serves to assist in separating charge carriers; migration (of all types) of oxygen vacancies from one part of the interface to another; transferring photo-excited electrons from the generated band of the oxide overlayer/superlattice into the conduction band of STO [11,49,20,16,17,29]. All of these effects collectively contribute to greatly enhanced and overstated photoconductivity commonly found in many heterostructures using STO as their substrate.

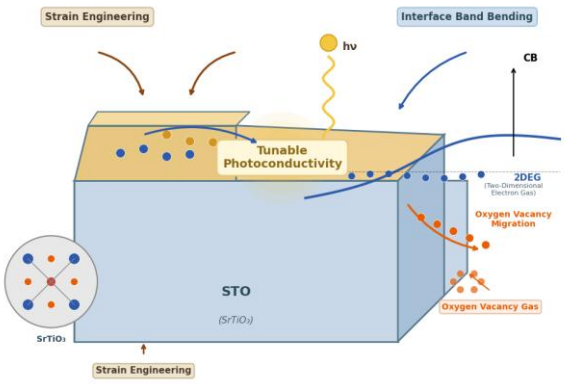


Figure 1. Role of $SrTiO_3$ (STO) as an active substrate. Schematic illustration of how strain engineering, band bending, oxygen vacancy migration, and formation of a two-dimensional electron gas (2DEG) at the heterointerface enable tuning of the photoconductivity of an overlayer.

3.1 Strain Engineering:

One of the key properties of Strontium Titanate (STO) is its near-perfect lattice matching (3.905 Å) to a variety of perovskite oxides, such as $LaAlO_3$, $SrRuO_3$, $BaTiO_3$ and $La_{1-x}Sr_xMnO_3$; therefore, they can be produced with atomically flat surfaces when grown epitaxially on top of these materials. Depending on the bulk lattice constant of the oxide being grown, the STO can either provide tensile or compressive forces on the films being deposited onto it, which in turn influences the electron properties (e.g., band dispersion, effective mass of carriers) such as photoconductivity and can be further altered through lattice strain. In particular, oxide films that are strained can undergo changes in the lengths of the metal-oxygen bonds and the tilt angles of the octahedra that can alter the amount of crystal field splitting and thus bandwidth. In turn, this modifies the optical absorption edge and the pathways for carrier relaxation [49-58]. In addition, tensile strain can reduce the band gap of transition metals and increase their optical absorption while compressive strain stabilizes localized states, which increases the time of the photoconductivity response [49,58]. Furthermore, recent studies suggest that the application of epitaxial strain to the oxide alters the thermodynamics of defect formation, specifically the formation energy of oxygen vacancies. Experiments and theoretical work have demonstrated the formation energy of oxygen vacancies is reduced through the application of epitaxial strain at the interfaces of the STO [18,54]. Therefore, a greater understanding of the coupling of strain and thermodynamics of defects will provide insights into understanding photo-induced conductivity and permanent photoconductivity in oxide/STO heterostructures.

3.2 Interfacial Band Alignment and Charge Transfer:

The use of strontium titanate (STO) is not confined to its structure but rather encompasses a critical role that involves the alignment of the conductance and valence bands via their respective energy levels [29]. The conduction band minimum (CBM) of STO is made up primarily by the Ti 3d states and is at a favourable position that allows for the transfer of electrons upon excitation from many oxide overlayers via optical means [8,12]. Band bending occurs when an oxide layer is deposited on top of the STO substrate due to differences in work function and/or electron affinity; thus, creating a built-in electric field that separates the photoexcited electrons and holes created in the film [13]. When a film is illuminated by light, the electrons generated in the film can migrate into the STO conduction band whereas the holes remain trapped either in the film or at the interfacial states. The separation of these carriers suppresses recombination and significantly extends the lifetimes of the carriers, resulting in an increase in the photoconductivity of the film. In many cases the photoconductivity persists long after the illumination source has been removed [15,21]. In addition, such behaviour has been observed at both polar/non-polar interfaces ($LaAlO_3$/STO) as well as in non-polar oxide films where the band bending at the interface is sufficient enough to drive charge transfer [16]. Importantly, the role of the STO substrate is greater than just being a conductive substrate; the very high dielectric constant of STO shields the Coulombic interactions between the carriers thus reducing the scattering of the carriers and allowing for high mobility of the transferred electrons [9,42]. Therefore, the efficient separation of charges combined with the mobility of the carriers within the STO makes the substrate an active participant in the photoconductive behaviour rather than just being a passive support for the oxide thin film.

3.3 Oxygen Vacancy Exchange and Photoinduced Defect Dynamics:

Oxygen vacancies are mobile in strontium titanate (STO) and, therefore, function as weak donors by introducing localized states in the band gap [10]. Due to the inherent mobility of oxygen vacancies, they can migrate in and out of amorphous films and/or their interfaces with STO during thin-film growth under low oxygen partial pressure or after growth has been completed when illuminated with light, resulting in real-time changes to the electronic properties of the film [17,20]. Because they are both free carriers and trapping sites, oxygen vacancies are involved in the coupling of photoconductivity to vacancy migration and, therefore, influence recombination kinetics of electrons trapped at these vacancies. While illuminated, photoexcited electrons are able to stabilise oxygen vacancies in STO by screening their positive charge, reducing the energy barriers associated with vacancy formation and migration [3,5]; this effect results in the creation of metastable and photo-induced states, causing many electrical properties to be improved for long period of time after the illumination event has ceased. This type of persistent photoconductivity has been commonly reported for STO-based heterostructures and has been attributed to a combination of vacancy movement throughout the heterostructure, charge trapping at the interface, and lattice deformation/relaxation [3,5,19]. Since the defect chemistry and electronic properties of STO are crucially linked to its ability to facilitate the movement of oxygen vacancies, STO has many opportunities for controlling the electronic properties of photoconductive devices by adjusting the growth conditions, annealing conditions, and the wavelength of the light source used to produce photoconductivity, thereby allowing for the tuning of vacancy population and, as a result, the modulating of the population of charge carriers, the speed of the response, and the time to return to the equilibrium state following the activation event [20]. These findings suggest that STO can be used as a substrate, as well as a functional part of photoconductive oxide devices due to the importance of its defect chemistry and electronic properties for designing these types of devices [6,15].

4. Polar Oxides Grown on $SrTiO_3$:

Polar oxide heterostructures that are grown on $SrTiO_3$ (STO) have been called one of the most extensively researched types of materials that demonstrate unconventional photoconductivity [15,21]. The key feature of these materials is that they contain alternating planes of atoms that are oppositely charged, which means there is an inherent discontinuity in polarization across interfaces with non-polar STO the substrate material [26]. The discontinuity in polarity results in electronic reconstruction, defects, and major band-bending occurring across the interface; each of which plays an important role in the nature of the photoinduced transport [12,13,29,26]. Of the polar oxide heterostructures mentioned above, $LaAlO_3$/STO has become well known and studied extensively, while primary and similar interfaces, such as $NdGaO_3$/STO and $LaGaO_3$/STO, offer comparisons to $LaAlO_3$/STO for additional insight [6,27,84].

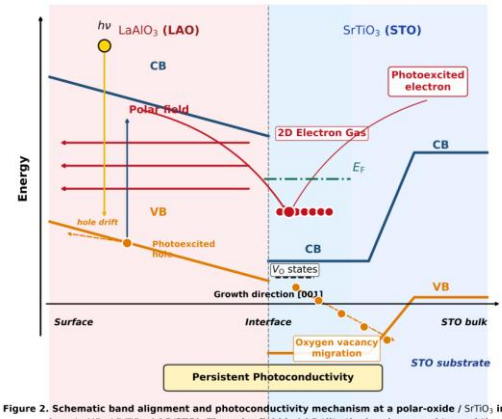


Figure 2. Schematic band alignment and photoconductivity mechanism at a polar-oxide / $SrTiO_3$ interface (e.g. $LaAlO_3$ / $SrTiO_3$, LAO/STO). The polar field in LAO tilts the bands upward toward the surface, driving photoexcited electrons toward the interface. Downward band bending in STO confines electrons in a 2DEG at the interface. Oxygen-vacancy (V_O) states and their migration contribute to persistent photoconductivity.

4.1 $LaAlO_3/SrTiO_3$:

The Lakeland/Tucson Discovery Site (LAO) is the most significant example of a polarized oxide layer that has been used as an alternative to semiconductors to achieve high, long hauls and efficient photo conductive connections. When LAO is four unit cells thick or greater in width, a two-dimensional electron gas (2DEG), which is located on the surface of the LAO layer at its junction with the surface of the STO region, develops due to excess charge. The electrons in the junction of these two regions exhibit an extremely high mobility, generally greater than 10,000 cm^2/V-s and greater than 60 times higher than the maximum value of typical semiconductor systems [6,22]. The long-lived nature of the 2DEG's conductivity (upon removal of the external light source) is a result of electronic charge transfer (polar discontinuity) due to the formation of an electronic reconstruction at the LAO/STO junction interface [6,15,26].The physical attributes of the junction also allow for high reactivity to incident energy; this means that the junction has been found to have a high degree of responsivity to optical excitation (e.g., UV or visible light), resulting in a high degree of photoconductivity [15,21,23]. More specifically, upon exposure to incident radiant energy, the electronic charge density in the LAO/STO junction interface can be increased by as much as a factor of 10 or greater (which happens even when exposed to room temperature ambient air) [15,21,23]. In addition, the long-term existence of the photoconductive state created from double-bonded LAO-derived charge carriers can be measured long after the source of the illumination is switched off, i.e., the photoconductive response is "non-volatile" independent of the incident light source [15,21].Transport measurements can also be used to characterize the rates with which charge carrier photoconductivity decreases at the LAO/STO junction as a function of time; these measurements show that photoconductivity decreases as a stretched-exponential decay (i.e., through a time-dependent mechanism of charge carrier trapping and relaxation through the presence of defects/interfacial states) [23]. Finally, multiple mechanisms contribute to the formation and existence of photoconductivity at the LAO/STO junction, including the generation of electron-hole pairs due to excitation by photon energy greater than the bandgap of STO and by virtue of the creation of trapped electrons in the LAO thin film by the existence of oxygen vacancy defects in the STO thin film [17,19]. In conclusion, in general, the mechanisms by which oxygen vacancies contribute to photoconductivity in LAO/STO can be summarized as follows: the presence of oxygen vacancies either by growing LAO films using low-pressure oxygen or via activating oxygen vacancy sites through excitation of the electronic states associated with the oxygen vacancy can lead to the accumulation of photogenerated carriers and depletion of carriers in the bulk of the LAO film [17,20]. Both the magnitude of the photoconductive response and the stability of the photoconductive response are highly sensitive to the conditions under which LAO films are grown. For instance, when LAO films are deposited using low-pressure oxygen, they form many oxygen vacancies within the STO, resulting in excessive photoconductive responses. Conversely, when LAO films are deposited using higher pressure oxygen, the formation of fewer oxygen vacancies results in the development of a more "intrinsic" and substantial photoconductive response at the junction interface [17,19,20]. Furthermore, after growth, cationic intermixing, interface termination, and post-growth annealing have a profound impact on band alignment and defect distribution; these phenomena demonstrate the precise relationship between electronic reconstruction of the LAO/STO junction and the contribution of point defect assisted processes, both of which have a dramatic impact on the performance of junctions comprising LAO and STO [26,29].

4.2 Other Polar Oxide Interfaces on $SrTiO_3$:

A number of other polar oxide interfaces that have been created using $SrTiO_3$ (STO) as a substrate have been discovered to be able to produce photoinduced conductivity

(photoconductivity), though, as is often the case, at a lower level than that produced by the $LaAlO_3$/STO interface. [27,29]. The results of direct electrical measurements performed on the NGO/STO and LGO/STO interfaces indicate that although these two systems can undergo electronic reconstruction, the level of enhancement of carrier density and photoconductivity produced by this electronic reconstruction at these interfaces is very small [27,84]. Photoinduced photoconductivity at the NGO/STO and LGO/STO interfaces has been shown to exhibit stronger dependence on both the wavelength and the temperature than at $LaAlO_3$/STO or other semiconductors, suggesting a much higher contribution from defect-mediated processes than from photoinduced processes. The physical characteristics of NGO and LGO as a result of their low dielectric screening and their different conduction band alignments when compared to STO will limit the amount of photoexcited electrons accumulated at their respective interfaces [27,84]. The findings for these two (2) interfaces further demonstrate that polarity alone will not produce a system with giant photoconductivity; instead, a combination of optimal band alignment and defect energetics is required [16,29].

4.3 Interface Band Bending and Carrier Trapping:

The primary characteristic of photoconductivity in polarized oxide/(STO) transition metal oxides is significant band-bending at the interface which results in strong spatial separation of photo-excited electron/hole pairs due to electrostatic potential gradient created at the interface enabling stronger photoconductive gain & PPCs via carrier trapping by interfacial & near-surface states, as they provide carriers with an additional means of obtaining sufficient carriers to support high levels of photoconductive gain/PPC /photoconductive) enhance carrier lifetimes and are necessary conditions for both large photoconductive gain and persistent photoconductivity (PPC) [16,21,29]. In addition, spectroscopic & transport measurements have identified many states that exist within the band gap related to oxygen vacancies, cation intermixing, and local structural distortions at the interface [17,18,29]. The presence of these defect-related states serves to create additional "reservoirs" of carriers and hence allow for slower release of carriers into the conduction band resulting in a "stretched exponential" relaxation dynamic & long-lived & long-persistent photoconductivity observed from polar oxide/STO heterostructures [19,21,23].

4.4 Implications and Outlook:

The role of interface engineering in oxide optoelectronic devices is shown by the photoconductivity of polar oxides that are deposited on $SrTiO_3$ (STO). By intentionally designing the interfacial properties of polar oxide layers and STO substrates, users can build heterostructures with customizable and permanent photoresponsive properties based upon deliberate engineering of interfacial polarity, band alignment, and defect distributions. Such precise engineering allows for a plethora of new device architectures to be developed such as optical memory devices, photo-gated FETs, and neuromorphic devices in which light is the external agent that programs and reprograms the electronic states of devices [32,42,56]. More generally speaking, the polar oxide/STO interfaces demonstrate a paradigm of photoconductive devices that form through coupling of the two materials at the interface rather than independently (the overlayer and substrate). The understanding of the coupling between the layers through photoconductivity will serve as a guide for investigating new types of oxide and hybrid heterostructures to provide a wider range of options for future use in optoelectronic and photonic devices [39,42,50].

5. Correlated Oxide Films on $SrTiO_3$:

Correlated oxide thin films deposited on $SrTiO_3$ form an important and highly varied type of photoconductive heterostructures where strong electron-electron interactions coexist with charge transfer mediated by the substrate. In contrast to traditional semiconductors, correlated oxides exhibit narrow bandwidths of the electronic states, competing electronic phases, and strong temperature dependence of their transport characteristics, making their electronic states highly sensitive to external disturbances such as light, stress, and electric fields. The effects of dielectric screening, band alignment, and defect chemistry of $SrTiO_3$, together with the competition between double-excitation and single-excitation processes in correlated oxides, result in an unusual photoconductive behavior for correlated oxide/$SrTiO_3$ heterostructures that cannot be accurately described by either a single-particle band model or a two-dimensional (2D) model [39,42,44]. The schematic shown in Figure 3 illustrates the four major features responsible for the photoconductivity of correlated oxide/$SrTiO_3$ heterostructures: photo-generated hot carriers in the correlated oxide film; interfacial charge transfer of electrons from the correlated oxide to the conduction band of $SrTiO_3$; and temperature-dependent transport pathways determined by electron correlations and competing electronic phases in the correlated oxide. Therefore, the connection between correlation-induced electron localization in the correlated oxide and the high-mobility transport of electrons in $SrTiO_3$ is a key factor in the development of significantly enhanced and sometimes persistent photoconductivity in these materials [15,21,33,38,42].

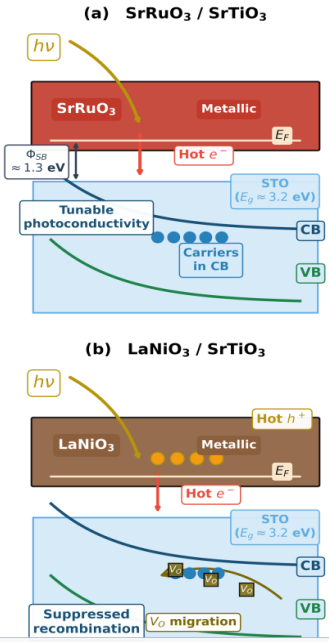


Figure 3. Band alignment and carrier dynamics at oxide interfaces. (a) In $SrRuO_3/SrTiO_3$, photons absorbed in the metallic $SrRuO_3$ film generate hot electrons that overcome the Schottky barrier ($\Phi_{SB} \approx 1.3$ eV) and inject into the $SrTiO_3$ conduction band, increasing carrier density and enabling tunable photoconductivity. (b) In $LaNiO_3/SrTiO_3$, photons absorbed in the metallic $LaNiO_3$ film generate hot carriers; hot electrons inject into the $SrTiO_3$ conduction band while hot holes remain in $LaNiO_3$, and oxygen vacancy (V_O) migration toward the interface suppresses electron-hole recombination, giving rise to persistent photoconductivity.

5.1 $SrRuO_3/SrTiO_3$:

$SrRuO_3$ (SRO), is a typical correlated metal oxide that is made from itinerant (mobile) 4d electrons and has large Hund's interaction and intermediate electron-electron interactions. Because of the chemical stability, low resistivity, and good lattice proximity to $SrTiO_3$ (STO), SRO is an essential conducting electrode in oxide electronic devices. Despite being a metal, SRO generates substantial photoresponses when incorporated with STO demonstrating that the photo-conductivity from SRO is largely connected to interface and substrate mediated phenomena and a small amount is generated by the film itself [81,36]. During optical excitation, especially in the visible and near ultraviolet spectral ranges, hot-carriers out of equilibrium energies are produced in SRO from both intra-band and inter-band electronic excitation processes. The presence of strong electron-phonon coupling in SRO produces rapid thermalization (decreasing the energy of carriers until they reach the equilibrium temperature) of the carriers, but some of these energetic electrons are able to traverse the interface potential barrier and are able to rapidly inject into the conduction band of STO resulting in the formation of a high-mobility photoconducting channel at the interface on the STO side similar to an internal photo-emission phenomenon at metal-semiconductor junctions [29,36]. The efficiency of the hot-electron injection process is related to the SRO film thickness with charge transfer across the interface enhanced in ultra-thin films due to confinement effects and changes in the films electronic structure producing higher photoconductive gain. In contrast, photoconductive gain decreases in thick films as carriers relax and dissipate energy into the bulk [82]. In addition, temperature plays a significant role in modifying the photoresponse, below the SRO ferromagnetic transition temperature (approximately 160 K) variations in spin polarization, scattering mechanisms, and carrier lifetimes can greatly influence photoconductivity [38,,36,81-83]. This demonstrates the complex interplay between electronic correlations, magnetism, and substrate aided transport in SRO/STO heterojunction systems. Additionally, it has been observed that the photoconductivity of SRO/STO heterojunctions has a very slow temporal relaxation once the illumination has occurred. This slow relaxation indicates that carriers become trapped at interface states or defect sites in the STO volume especially those involving oxygen vacancy sites which will stabilize the photo-excited electrons leading to persistent or quasi-persistent photoconductive states. Therefore, the STO is significant not only for being a high-mobility transport medium, but also as an active charge reservoir which controls the temporal evolution of the photoresponse [81,82].

5.2 $LaNiO_3/SrTiO_3$:

$LaNiO_3$ sits in an interesting electronic regime where its electrons are neither fully localised nor completely itinerant. Instead, they occupy a middle ground where strong correlations dominate the physics. In ultrathin films, this behaviour becomes even more pronounced because the electronic structure is no longer simply a bulk property. It shifts noticeably depending on film thickness, how much the lattice is strained during growth on $SrTiO_3$, and which crystallographic face of the substrate is used. These factors—thickness, strain, and interface chemistry act as tuning knobs that push the system toward either metallic or insulating behaviour. Experimentally, this means an ultrathin LNO film on STO can be driven across a metal–insulator transition by adjusting any of these parameters, and the transition itself remains highly responsive to external perturbations such as electric fields, epitaxial strain, or interfacial reconstruction [33,40,41]. The band alignment at the LNO/STO junction is favourable enough that electrons generated in the nickelate layer can transfer into the STO conduction band [29], where they encounter a much cleaner transport channel with reduced scattering [9,42]. STO also brings its large dielectric constant into play, screening Coulomb interactions and suppressing electron–hole recombination. As a result, carriers can persist well after the excitation source is removed [9,42]. However, the picture is not without complications. Oxygen vacancies in the STO substrate introduce trap states that capture electrons and release them only slowly. This gives rise to a quasi-persistent photoconductive response similar to what has been observed in other STO-based heterostructures [17,19,20,87]. Transport measurements further reveal that the system is highly sensitive to small changes in carrier density, lattice distortion, and orbital occupancy, all of which vary with temperature and film thickness. Taken together, the exceptional tunability of LNO/STO through thickness, strain, and electric field makes

it a promising platform for adaptive oxide electronics and optoelectronic devices [42,44].

5.3 Broader Implications of Correlated Oxide/$SrTiO_3$ Interfaces:

Both the $LaNiO_3/SrTiO_3$ (STO) and $SrRuO_3/SrTiO_3$ (STO) heterostructures display clear indications that correlated oxide materials in contact with a STO demonstrate distinctly different mechanisms of photoconductivity relative to traditional types of semiconductor heterojunctions. In these types of heterostructures, optical excitation acts as an additional source of charge carriers, as well as an active perturbation that changes the balance of electronic phases competing with each other, redistributes charge at the heterosurface, and takes advantage of the inherent dielectric screening properties of STO and the defect landscape in STO, as well as the mobility of the carriers in the STO lattice [3,5,9,36,44,81-83].The strong coupling between the dynamics of nonequilibrium carriers and the competition between electronic phases (i.e. correlated phases) is a unique feature of the photoconductivity of correlated oxide materials in contact with STO. Close to points of electronic instability (e.g., metal to insulator transitions, magnetic phase transitions), a change in the number of carriers available to participate in a physical process (such as the formation of non-canonical ground states) and/or a change in the orbital character of a carrier in a correlated oxide, can aggravate the relative stability of heterogeneous states that compete with correlated states, which can lead to very large changes in the measured conductivity of a specific material in the heterostructure [33,39-41,44]. The increase in the measured conductivity values within these heterostructures may also be enhanced by the inherent dielectric screening properties of the STO substrate, which stabilizes the photogenerated electrons and increases the probability of the formation of long-lived or metastable conductive states via defect-assisted trapping [3,5,9]. Photogenerated changes associated with photoconductivity in correlated oxide/STO heterostructures create very intriguing possibilities for the development of new optically tunable devices. Potential examples of optically-tunable devices include photo-controlled resistive switching; optically-gated transistors; spintronic devices; and neuromorphically-inspired components [32,51,56,63-65]. All of these systems have the potential to exploit the interaction of correlated electron physics with dielectric screening in the fabrication of charge storage. In another sense, the correlated oxide/STO heterostructure provides experimental platforms which contain many of the same features that will be present in real materials with strong-coupling correlated systems (e.g., strong-coupling effects, structural effects, and functional effects all produced by the boundary conditions between layers). Therefore, the correlated oxide/STO heterostructure provides researchers with a valuable tool for the study of the impact of nonequilibrium dynamics on complex coupled systems [33,39-44].

6. Ferroelectric Oxides on $SrTiO_3$:

Ferroelectric oxide films, which have been deposited on $SrTiO_3$ (STO) substrates, offer an added level of control over photoconductivity via a new form of switching based on spontaneous polarization. Whereas in the case of polar or correlated oxides, inherent electric fields arise from either a polar lattice structure or from electronic reconstruction, ferroelectrics are able to maintain intrinsic polarization that can transition between two states when exposed to an external electric field. Additionally, this polarization-switching mechanism also enables ferroelectrics to directly modulate: 1) interfacial band alignment; 2) carrier separation at the interface; and 3) transport of photogenerated carriers from ferroelectric material into STO. All these effects lead to nonvolatile and polarization-controlled photoconductivity [54-55]. Furthermore, the coupling of ferroelectric polarization with the electronic properties of STO leads to significant changes in the generation, separation, and recombination dynamics of photogenerated carriers. Polarization oriented either toward or away from the STO film results in upward or downward band bending, respectively, with respect to the interface of the two materials. The direction of the band bending ultimately dictates whether photogenerated electrons will be injected into the conduction band of the STO or whether they will remain trapped within the ferroelectric film at the interface, both of which greatly impact the overall efficiency and directionality of photoinduced charge transfer [50,55,56]. As shown schematically in Figure 4, the band bending described above provides a mechanism for either optical or electric energy inputs to work jointly to produce a reconfigurable photoresponse which is stable after the removal of both light and electric fields. Thus, ferroelectric/STO heterostructures represent an ideal medium for creating nonvolatile optoelectronic memory, photo-gated transistors, and adaptive electronic systems in which light and polarization together determine their electronic state [32,51,56].

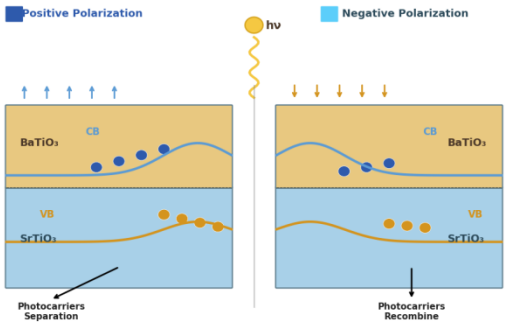


Figure 4. Polarization-controlled band alignment and photoconductivity at a ferroelectric/$SrTiO_3$ interface (e.g., $BaTiO_3/SrTiO_3$), illustrating how positive polarization promotes photocarrier separation while negative polarization triggers photocarrier recombination.

6.1 $BaTiO_3/SrTiO_3$:

The ferroelectric oxide $BaTiO_3$ (BTO) has been the most widely researched ferroic oxide that pairs with stoichiometric $SrTiO_3$ (STO); hence BTO is often used as a reference system for comprehending photoconductivity that is induced by polarization in oxide heterostructures. The high degree of similarity between BTO and STO as they exhibit similar crystal structure and both contain perovskite structure allows for an easy to create high-quality epitaxial BTO thin films on STO with coherent interfaces, limited defect density, and clearly defined ferroelectric polarization states [49,52].The orientation of the ferroelectric polarization in BTO/STO heterostructures significantly influence the amount and permanence of the photoconductive response produced. When the polarization points toward the STO substrate (down the ferroelectric polarization vector), downward band bending on the STO side of the interface occurs, resulting in the efficient transfer and accumulation of photoexcited electron into the conduction band of STO. This produces a greater charge separation and prevents any recombination of electron-hole pairs, thereby increasing the photoconductivity and the length of time for which the charges may separate into the substrate without recombining [50,55]. When the polarization points away from the interface, the upward band bending at the interface hinders the injection of photoexcited electons from the BTO into the STO and creates a much lower level of photoconductivity. Several experimental studies have established that optical illumination creates significant, and may be reversible, changes in the conductivity as a consequence of the polarization state of the BTO layer. This may be used to produce a light-sensitive, nonvolatile electronic switch. More importantly, the photoconductive response that is controlled by the polarization state persists after the illumination has stopped due to the stabilization of the photo-excited carriers by the internal ferroelectric field and the strong dielectric screening provided by the STO substrate [54,55]. The ability to generate a nonvolatile and reprogrammable photoconductive response indicates that BTO/STO heterostructures represent excellent candidates for use as optoelectronic memory cells, photo-gated transistors, and adaptive oxide electronics [32,51,56].

6.2 Polarization-Controlled Band Alignment and Carrier Dynamics:

The primary photoconductive properties of ferroelectric/$SrTiO_3$ (STO) heterostructures are a result of band alignment changes at the interface caused by polarizations applied by the ferroelectric. An applied ferroelectric polarization creates an electrostatic potential (+) within the ferroelectric that "donates" electrons and alters the alignment of conduction and valence bands at the interface [50,55]. Additionally, the polarization changes the energy barrier between the two bands at the interface allowing for the control of electron and hole movement from the ferroelectric to the conduction band of the STO when illuminated. The electric nature of the charge carriers that arise from the illumination of the ferroelectric or the underlying STO will depend on the operational condition of the ferroelectric's polarization. The polarization of the ferroelectric "creates" fields that promote charge carrier separation. For example, if the polarization is oriented to promote electron accumulation at the interface, then the photoexcited electrons created by illumination of the ferroelectric will easily transfer to the conduction band of the STO and have high carrier mobilities and strong dielectric screening. However, the opposite is true for the holes that are created in the ferroelectric under the same polarization condition. Under this condition, the holes created by illumination will either become trapped in the ferroelectric, or at the interface, thus resulting in a large amount of dispersed spatially; therefore there is little opportunity for recombination [50,55,56].The separation of the electrons and holes created results in longer carrier lifetimes and consequently more gain associated with photoconductivity. Additionally, the interaction of the ferroelectric polarization will aid in the dynamics of the neutral oxygen vacancy located in the STO; for example, the oxygen vacancy will have a positive charge associated with it. Thus, if the ferroelectric is polarized positively, the oxygen vacancy will be attracted to the interface and focused toward it; conversely, if the ferroelectric is polarized negatively, the oxygen vacancy will be repelled from the interface. Therefore, the concentration of oxygen vacancies is redistributed as a function of the polarization of the ferroelectric and results in enhanced photoresponse of the ST-ferroelectric heterostructures. When using an oxygen vacancy as either a relatively shallow donor or trapping center for an electron, the electron that is captured in an oxygen vacancy will stabilize the photoexcited electron and cause persistent photoconduction under illumination with a slow relaxation time [20,54]. By employing the tunable band alignment together with charge carrier separation and the ability to generate and position oxygen vacancies under illumination, Ferroelectric/$SrTiO_3$ (STO) heterostructures offer a unique, non-volatile, and highly tunable photoconductive characteristic [32,51,54].

6.3 Other Ferroelectric Oxides on $SrTiO_3$:

The application of different ferroelectric oxides with $SrTiO_3$ (STO) other than $BaTiO_3$ has increased the ability to manipulate photoconductivity through applied polarizations. $Pb(Zr,Ti)O_3$ (PZT) is the most widely used ferroelectric photoconductor capable of producing a response based on the polarization of the material when utilizing an STO substrate. In fact, PZT/STO hybrids yield enhanced photocurrent due to the polarization orientation favour directed electron transfer to the STO substrate, indicating the role of PZT polarization in driving both aggregate charge separation and band bending at the interface [50,55,56]. PZT is not the only known ferroelectric material that influences

photoconductive behaviour; both $KNbO_3$ and $BiFeO_3$ films also show the effect of ferroelectric polarizations when structured onto STO substrates. In $KNbO_3$/STO, the charge carrier injection and recombination are dictated by the change in band alignment of the $KNbO_3$ due to polarization [87]. In the case of $BiFeO_3$, while the antiferromagnetic ordering and relatively small bandgap of $BiFeO_3$ also play important roles in light absorption and generation of photon-generated carriers, the photoconductivity is still largely determined by the polarization of the $KNbO_3$ that it is grown on [55-57]. While each of these materials may differ in their individual characteristics, the common behaviour of separating photon-generated carriers as a result of polarization creates an efficient high mobility transport path (STO) and reservoir of charge carriers (STO). The magnitude and stability of the observed photoconduction effects are dependent on three main factors: ferroelectric polarization, epitaxial strain imparted by the substrate, and defect chemistry at the interface. Application of strain provides a means of enhancing spontaneous polarization; control of domain structure; and shifting the temperature at which the ferroelectric transitions occur, which will all subsequently contribute to the enhancement of the PZT photoconductivity produced by each system [50,55,56,49]. The ability of the substrate to act as a structural template, an electronic mediator, and an approach to stabilize photo-induced states demonstrates the strong coupling between the substrate's many multifunctional characteristics [42,50].

6.4 Implications for Optoelectronic Devices:

Ferroelectric oxide/$SrTiO_3$ (STO) heterostructures provide innovative possibilities for optoelectronic device functionality that utilize conductivity controlled by light and ferroelectric polarization. The ability of ferroelectric polarization to retain its state for long periods of time allows for the development of optical memory devices that can be written and read through electrical and optical means, respectively [32]. Dual-mode operation is typically unattainable in mainstream semiconductor devices, giving ferroelectric/STO materials a distinct advantage. In addition to memory devices, polarization-tunable photoconductivity also provides the basis for photo-gated transistors, reconfigurable logic devices, and adaptable optoelectronic circuits using light to modulate the conductivity of the device channel while using ferroelectric polarization to determine both the steady-state electronic state of the device and its nonvolatile functionality. The performance of these resulting devices is further enhanced due to the high occurrence of carrier mobility due to the strong dielectric screening of the STO oxide layer, yielding lower scattering losses and longer-lived photoexcited carriers than most commercially available devices [22]. More expansively, these ferroelectric/STO systems demonstrate how internal electric fields can be used to control the nonequilibrium carrier dynamics with the complex oxide interface region. By combining switchable ferroelectric polarization with the charge storage and transport characteristics of defects in STO, these materials provide a potential basis for multifunctional oxide optoelectronics that integrate electronic memory [42,47,51,59], photodetection, and adaptive processing of information with the same materials platform [32,63,65,81].

7. Semiconductors and Two-Dimensional Materials on $SrTiO_3$:

Combining traditional semiconductors and new two-dimensional (2D) materials on a strontium titanate (STO) substrate has produced new mechanisms of achieving unusual and elevated rates of photoconductivity. In the case of hybrid devices containing both a "traditional" semiconductor and a 2D material connected to the strontium titanate substrate, the strontium titanate does not simply serve as an inactive substrate, but rather as an active electrical device, because the addition of various 2D materials (and/or other types of semiconductor materials) provides a suitable platform for separating charge carriers and optimising the lifetime of those carriers after they are generated. In addition, by creating defects and traps at the interface between the materials, it is possible to prolong the duration of photoconductivity after initial generation. In contrast to oxides that can only interact with other oxides, the interfaces between the semiconductor and strontium titanate (as well as between the 2D material and strontium titanate) present different electronic structures that can allow for the production of band alignments by utilising multiple light wavelengths across the entire photon energy range (from ultraviolet to near infrared)[60,62]. Photoconductivity in the hybrid strontium titanate/semiconductor and strontium titanate/2D structures takes place as a result of exciting electrons from the semiconductor or 2D material's valence band with light. The effectiveness of this process is related to the fact that STO has a much greater energy "band gap" than most conventional semiconductors or 2D materials; therefore, traditional semiconductors and 2D materials are much more efficient than STO for absorbing light. Once electrons have been produced as a result of light absorption in the semiconductor or 2D layer, they will move from the valence band of that semiconductor or 2D layer across to the conduction band of the STO as a result of an appropriate band offset created at the interface between the semiconductor and the STO (in addition to an electrical field created at that interface) [60,62,69]. Once in the conduction band of the STO, the very high mobility of the electrons and the dielectric constant of the STO will result in very low levels of Coulomb scattering and will help to deter charge carriers from returning to their original positions [22,62]. Thus, the photogenerated holes generated in the semiconductor or 2D layer will remain in those layers for a longer time period, leading to a long period of charge separation and a much greater enhancement in photoconductivity [60,69].

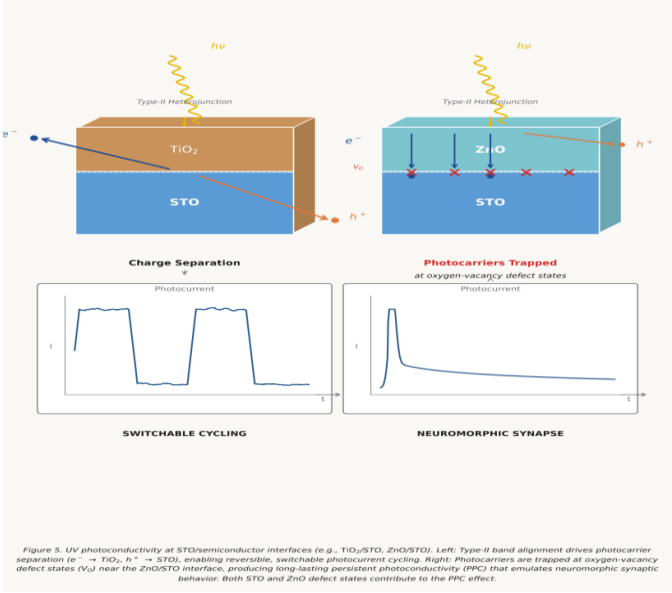


Figure 5. UV photoconductivity at STO/semiconductor interfaces (e.g., TiO_2/STO, ZnO/STO). Left: Type-II band alignment drives photocarrier separation ($e^- \rightarrow TiO_2$, $h^+ \rightarrow$ STO), enabling reversible, switchable photocurrent cycling. Right: Photocarriers are trapped at oxygen-vacancy defect states (V_O) near the ZnO/STO interface, producing long-lasting persistent photoconductivity (PPC) that emulates neuromorphic synaptic behavior. Both STO and ZnO defect states contribute to the PPC effect.

7.1 Wide-Bandgap Semiconductors on $SrTiO_3$:

Wide-bandgap semiconductors such as TiO_2, ZnO, and Ga_2O_3 integrated with $SrTiO_3$ (STO) are promising materials for ultraviolet (UV) photodetection and enhancement of the photoresponse due to their strong intrinsic absorption of UV wavelengths and the ability of STO to provide an excellent substrate for the transport, dielectric screening and stabilization of defect-assisted carriers [10,63,79,80]. The combination of these heterostructures is beneficial because it allows for the efficient creation of photogenerated carriers in the wide-bandgap semiconductor and the long-lived nature of the carrier dynamics through the use of the underlying STO substrate. In TiO_2/STO heterostructures, UV illumination primarily creates electron-hole (e-h) pairs in the TiO_2 layer. Because the conduction bands of the two materials are well aligned at their interface, the photo-generated e^- are efficiently transferred into the conduction band of the STO substrate, while the photo-generated h^+ remain either trapped in the TiO_2 or at interfaces [10,62]. The spatial separation of these two carrier types significantly reduces the probability of radiative and nonradiative recombination, leading to large increases in the photoconductivity and time for carrier decay. In addition, the presence of oxygen vacancies in the STO substrate further enhances these effects by also acting as shallow donors and trap sites for the photo-generated carriers, thus stabilizing the photo-induced conductive states and ultimately contributing to the overall enhancement of photoconductivity [5,10,65]. ZnO/STO heterostructures exhibit a very similar photoconductivity response to UV illumination and have a strong sensitivity to UV wavelengths and also to persistent photoconductivity. The large exciton binding energy of ZnO allows for a larger number of photo-generated carriers to be created, while the STO provides an efficient sink for the e^- generated by the uv illumination and allows for high mobility transport between the conductive layers and a significantly extended carrier lifetime [67,79,80]. Importantly, the magnitude and transient nature of the photoresponse from ZnO/STO heterostructures is very sensitive to the oxygen partial pressure during the time of growth and post-deposition annealing treatments. The sensitivity of the ZnO/STO heterostructures to the oxygen partial pressure indicates that the interfacial defect chemistry of the two materials, particularly the presence of oxygen vacancies, plays a significant role in determining the carrier transfer, trapping and recombination dynamics [5,19,60,67].

7.2 Substrate-Assisted Persistent Photoconductivity:

A common feature exhibited in many semiconductor/STO heterostructures is the appearance of persistent photoconductivity (PPC) as seen by a slowly recovering or non-exponentially decaying conductivity after turning off illumination. PPC in semiconductor/STO heterostructures differs from PPC commonly found in bulk semiconductor materials through its reliance on substrate assistance, which can be attributed to the interplay of interfacial band bending and defect related trapping found within the STO material [16,17,60]. When the semiconductor layer is optically excited, the photogenerated electrons will move from the semiconductor conduction band to the conduction band of the STO layer, while the holes will be left to either be confined to the semiconductor conduction band or be trapped at the interfacial region of semiconductor/STO heterostructures. The spatial separation of charges caused by this process inhibits recombination of the photogenerated charge carriers. In addition, because the dielectric constant of STO is extremely large, the Coulomb interactions are effectively screened; as a result, the interaction energy between electron and hole will be low, which allows the charge carriers to continue to exist for much longer periods of time [22,62]. Additionally, defect states in STO, particularly oxygen vacancies, are critical to the overall behavior of the PPC in these materials. Oxygen vacancies act as metastable trapping centers that will capture photogenerated electrons and release them for a limited time using thermally activated processes. The result of these trapping processes will produce a stretched exponential or logarithmic decay rate of the observed photoconductivity due to a broad distribution of trap depth and lifetime observed in time-resolved transport measurements [10,19,23]. Also of importance is that PPC is very tunable by varying the different parameters used to generate the PPC; such parameters can include changing the wavelength of the excitation, changing the intensity of the illumination, changing the temperature of the semiconductor/STO heterostructure, and varying the concentration of the oxygen vacancies. By utilizing these types of variations the magnitude and relaxation dynamics of the photoconductive response can be systematically controlled [17,19,69].Overall, the large degree of tuning we have for PPC, combined with the long-lived nature of the conductive states, suggests that semiconductor/STO heterostructures have the potential to be used to create optically programmable electronics,

memory devices, or other adaptive photonic devices [32,60,69].

7.3 Two-Dimensional Materials on STO:

The creation of two-dimensional (2D) materials has led to new opportunities for utilizing substrate-mediated photoconductivity when they are incorporated into sodiuem titanate ($SrTiO_3$ or STO). The 2D materials exhibit optical and electrical properties that can be greatly affected by the interface they are bonded to and the transfer of charge induced by the substrate. Substrates such as STO have an active role in controlling how photocarriers are generated and transported within semiconducting and semi-metallic 2D materials like MoS_2, WS_2, and graphene when they are placed on an STO surface [61,62,69,70]. In the case of MoS_2 on the STO heterostructure, the absorption of light will primarily produce tightly bound excitons within the MoS_2 material. The excitons produced can either photonically dissociate at the MoS_2/STO interface or can be transferred into the conduction band of the STO if they travel through a boundary that experiences dielectric screening and band bending due to the STO [9,62,69,76]. The STO substrate has a very high dielectric constant and thus reduces the exciton bound state energy in MoS_2 effectively increasing the efficiency of the charge separation between the two regions and reducing the amount of recombination that occurs. Additionally to this, the photocurrents generated in the MoS_2/STO heterostructures are much greater than that generated when the MoS_2 is put on other types of insulating substrates. Studies of the electrostatic gating of MoS_2 devices equipped with STO substrates also demonstrate the multiple functions that the STO serves in a MoS_2 optoelectronic device [61,76]. The STO substrate provides a large dielectric constant allowing for effective charge modulation at low gate voltages. When light exposes the heterostructure, the photogenerated charges are stored in the STO and can be released from the STO into the last layer of MoS_2 upon bias application. Therefore, the ability to control how these charges will interact with the MoS_2 material by utilizing the electric field generated by the application of a bias to the STO signifies very strong interactions between the photo-excitation of the MoS_2, the transfer of charge between each material at the interface, and the charge accumulation in the STO [61,62]. The photoconductivity of graphene heterostructures on STO exhibit a similar but distinct substrate-induced photoconductivity mechanism. Due to the fact the graphene does not have a bandgap and absorbs very little light, the majority of photoconductive activity in these systems is dominated by a photogating mechanism rather than from direct photogeneration of carriers in graphene itself. When illuminated, the carriers created by the light in either own or from defects in the STO substrate at or near the interface will change the electrostatic potential in their locale and thus will change the carrier density and conductivity in the graphene channel [74,77]. The phototransduction mechanism outlined above, provides graphene on an STO substrate with the ability to produce a broadband phototransduced signal, have high sensitivity, and have long-lived conductivity changes, indicating that graphene on an STO substrate are very versatile functional components for 2D optoelectronic systems [74,77].

7.4 Interface Engineering and Device Implications:

The photoconductive activity of the heterostructures of oxide/n-Semiconductor and oxide/2D materials, which include wide bandgap semiconductor with strontium titanate (STO) as well as thin film materials such as graphene, MoS_2, and WSe_2 with STO, depends on the quality of the interfaces, the alignment of the bands, and the distribution of defects. Atomic-scale defects at the interface, such as dangling bonds, surface roughness, and the distribution of oxygen vacancy concentrations, can impact the efficiency of charge transfer and the lifetime of carriers. Therefore, way to optimize and stabilize the photoconductive response have been created through engineered interfaces [16,17,62]. Interface passivation (e.g. surface modification techniques or through the use of ultrathin dielectric or oxide buffer layers) are effective in reducing the number of non-radiative recombination centers while maintaining the desired alignment of the bands. Controlled oxygen vacancy engineering in STO has also proven effective (e.g. through the use of an optimized growth atmosphere, post-deposition annealing, or electrochemical gating) in allowing fine tuning of the carrier density, the trapping dynamics, and the photoconductive gain of devices [17,20,65]. These techniques also significantly improve the reproducibility of devices, which makes them suitable for practical applications. In terms of applications, heterostructures composed of n-type semiconductors or 2D materials on strontium titanate are versatile heterostructures for optoelectronic devices, with wide bandgap semiconductor - strontium titanate heterostructures being attractive candidates for high sensitivity and long retention time ultraviolet photodetectors, and optically gated transistors and photogating-based sensors with low power consumption and broad wavelength response can be made by interfacing 2D materials to strontium titanium oxide [60,63,74]. Hybrid structures (combinations of mechanical flexibility and tunability associated with semiconductors or 2D materials, with high carrier mobility, type of dielectric screening, and the function of defects associated with strontium titanium oxide) can be a very promising route toward next-generation optoelectronics [42,60,62]. More broadly, this work illustrates that photoconductivity in strontium titanium oxide is not limited to all-oxide heterostructures and that it serves as a general principle for enhancing photoconductive response across classes of materials by carefully controlling the electronic structure at the interface and the chemistry of the defects at the interface [42,60,62].

8. Comparative Summary of STO-Based Photoconductive Heterostructures:

This part combines various materials systems into one overview, making it easy to directly compare some of the most important properties of photoconductive compounds that have been grown on $SrTiO_3$ (STO). Comparative studies help us identify common trends, identify materials that have unique properties, and understand how STO functioned as an active substrate in many different types of heterostructures. While many electronic phases and the mechanisms for excitation are different from one another, there are some common phenomena among them as well; for example, the way that carriers are stabilized by defects, how substrate-induced band bending effects the transport of charge carriers, and how carriers are transported through the substrate (STO).

Table 1 Photoconductivity mechanisms in representative materials grown on STO substrates

Material system	Dominant mechanism	Spectral response	Persistence	Role of STO
$LaAlO_3$/STO	Electronic reconstruction + defect trapping	UV–Visible	Strong PPC	Hosts 2DEG, defect trapping [6,12,15,21–26,28]
$NdGaO_3$/STO	Polarity-driven band bending	UV–Visible	Moderate	Charge confinement, screening [16,26,27,29]
$SrRuO_3$/STO	Band-structure modulation (quantized metal)	Visible	Weak–Moderate	Transport channel, band bending [35,36,81–83]
$LaNiO_3$/STO	Carrier density modulation near MIT	Visible	Moderate	Charge reservoir, screening [33,40–44]
$BaTiO_3$/STO	Polarization-controlled alignment	UV–Visible	Strong (nonvolatile)	Polarization screening, stabilization
				[46,50,55,56]
PZT/STO	Switchable polarization photocurrent	UV–Visible	Strong	Interface band modulation [46,50,55,56]
TiO_2/STO	UV excitation + electron transfer	UV	Strong PPC	Electron sink, vacancy trapping [10,63,64,65]
ZnO/STO	Excitonic absorption + charge separation	UV	Strong PPC	High-mobility transport, defect mediation [60,62,67,79]
MoS_2/STO	Exciton dissociation + photogating	Visible	Moderate	Dielectric screening, charge storage [61,70,75,76]
Graphene/STO	Substrate photogating	Broadband	Weak–Moderate	Photocharge storage, electrostatic gating [62,70,74,77]

Table 2 Growth parameters, defect roles, and performance trends in STO-based photoconductivity

Growth method	Oxygen vacancy role	Typical response time	Tunability	Representative systems
Pulsed laser deposition (PLD)	High (pressure-dependent)	ms–hours	High	LAO/STO, SRO/STO
Molecular beam epitaxy (MBE)	Low–moderate (controlled)	ms–s	High	LNO/STO, BTO/STO
Sputtering	Moderate	s–min	Moderate	ZnO/STO, TiO_2/STO
Mechani	STO-	ms–s	Very	MoS_2/STO,

cal transfer (2D)	dominated		high	graphene/STO

Comparative Insights

From the comparison of previous results, three main patterns emerge across all types of materials: 1) STO consistently behaves as both an electron-acceptor and a stabilizing medium for electron carriers no matter what the overlayer type; 2) systems with interfacial band bending combined with defects that create traps have the strongest sustained photo-conductivity, such as polar oxides and wide-bandgap semiconductors paired with strontium titanates ; 3) the combination of strontium titanate with ferroelectric and/or 2D materials allows maximum tunability via two knobs: polarization from the ferroelectric and electrostatic gating. As such, it can be concluded from the above tables that all examples given (during reviews) refer to an interface-specific photoconductive phenomenon, not a specific type of material, thereby supporting this article's primary argument.

9. Applications and Device Concepts Based on STO-Mediated Photoconductivity:

There is a much broader class of devices that you can create based on the many different kinds of photoconductive phenomena that occur in $SrTiO_3$ (STO) based heterostructures than just the traditional semiconductor optoelectronics. Compared to traditional photo detectors where the photo response is determined by bulk absorption, depletion regions, and carrier diffusion, devices based on STO use interfacial charge transfer, defect-assisted stabilization of carriers, and internal electric fields to enhance the sensitivity and longevity of carriers, and in some cases, provide nonvolatile operation. Due to these unique properties, STO based heterostructures have a great potential to serve as fundamental elements for the development of next generation optoelectronics, memory, and neuromorphic technologies [39,42,51]. An important characteristic of photoconductivity associated with STO is that the optical absorption and carrier transport are no longer coupled together. When light is absorbed, the absorption generally occurs in the overlayer (oxide, semiconductor, or 2D material), while the majority of charges are transported through the STO, where the carriers benefit from high mobility and excellent dielectric screening [22,42,62,63]. The separation of where absorption occurs and where transport occurs allows for the formation of device structures with relatively low recombination losses and very high photoconductive gain even with ultrathin active layers [22,63]. In addition to this, the extreme sensitivity of STO to defects and applied electric fields and possible changes in polarization permits the tunability of device characteristics by adjusting growth conditions, applying electric fields, and/or applying illumination [20,69,73].

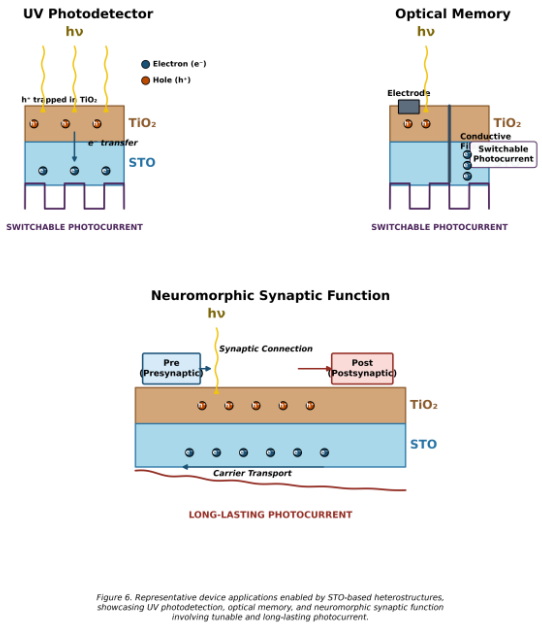


Figure 6. Representative device applications enabled by STO-based heterostructures, showcasing UV photodetection, optical memory, and neuromorphic synaptic function involving tunable and long-lasting photocurrent.

9.1 Photodetectors and Optical Sensors:

STO-based photoconductivity represents one of the two primary senses of operation for UV and visible photo dectors. The heterostructures have large responsivity due to efficient charge separation and suppressed recombination, and low noise, for example, those comprised of TiO_2/STO, ZnO/STO, and various polar oxides on top of STO [60,63,65]. Once the photo-excited electrons reach the conduction band of the STO, they can migrate with high mobility and exhibit strong dielectric screening that improves collection of these carriers [22,42,62].While some people see persistent photoconductivity (PPC) as limiting fast photo detection, it helps to improve sensitivity to low-light, radiation monitoring, and dosimetry applications through the integration of energy from temporally accumulated signals created by the combination of photoexcitation and thermal cycling over time [23,65,69]. This means that interface engineering, polarized illumination techniques, electrical gating, and thermal cycling can be used to control the PPC behaviour in photodetectors based on Strontium Titanium Oxide (STO) in whatever operational conditions may exist; therefore, the operational behaviour of these photodetectors may differ in response to varying operating conditions [20,39,42,73].

9.2 Optical Memory and Photo-Switching Devices:

The ability of many STO based heterostructures to exhibit optical non-volatile photoinduced conductivity lends itself to optical memories and photo-switch devices [32,60,65]. In typical ferroelectric/polar oxide/STO systems, when exposed to optical illumination, a high conductive state could be established which would remain even after the optical

light was turned off [60,65,69]. The high conductivity state could be erased or reset using thermal annealing methods or via electrical biasing [5,20,48]. Ferroelectric/STO heterostructures allow for an additional way of achieving multiple functionality as using an independent ferroelectric polarisation control combined with photoexcited carrier density allows for multiple levels of information to be encoded within a given cell [31,50,51]. Thus, simultaneously encoding information in both the orientation of the polarisation and the conductivity will result in higher density data storage and introduce new ways to operate transparent, oxide based, non-volatile memories. [32,47,51].

9.3 Photo-Gated Transistors:

Photoconductivity caused by STO has also been widely employed in a number of different transistors based on the use of photogates. The concept here is that the photogenerated charge carriers that are either stored at the STO surface or at the heterointerface provide a gate electric field which modulates the conductivity of a channel adjacent to it, using materials such as graphene, MoS_2, or an oxide semiconductor [60,63,65]. This innovative use of a secondary charge (i.e., photogenerated charges) to create a different gate electric field can result in the creation of photogated transistors with huge photogain and a broadband photoresponse, as there is no need for the channel material to absorb large amounts of light [72,74,81]. The use of materials with a high dielectric constant (here the use of Al_2O_3 and an oxide semiconductor) also increases the degree of electrostatic coupling between the stored photogenerated charge and the channel material thus generating high sensitivity and low voltage operation [22]. Furthermore, since photogenerated carriers can have a long lifetime, photogated transistors can exhibit memory characteristics thus allowing for new applications and providing a functional bridge between photodetectors and non-volatile electronic devices [32,65,69].

9.4 Neuromorphic and Synaptic Devices:

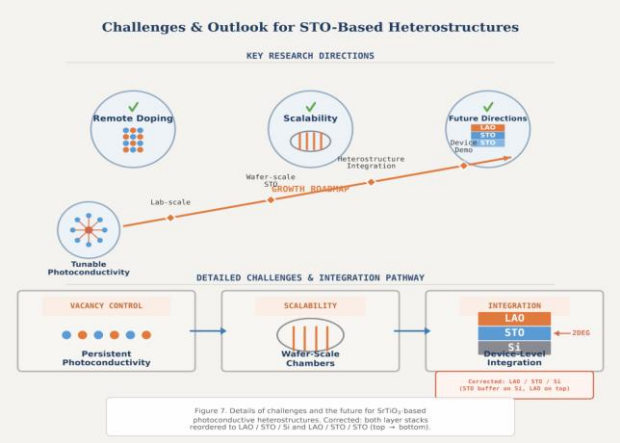
The kinetics of relaxing back to a stable state through a viscous process and the nonlinearity and dependence of the photoresponse of the strontium titanate (STO)-based devices on the history of their operation strongly resemble the synaptic properties of biological neurons. Thus, there is growing interest in using these materials for neuromorphic computing and brain-inspired computing applications [32,65,69]. In this instance, optical pulses are utilized as external stimuli to change the amount of photoconductivity, and thus modulate the synaptic weight [39,42]. These devices utilize several internal state variables (e.g., oxygen vacancies migrating, charge being trapped at the interface between the two materials, and the ferroelectric polarization of the materials) to control conductance on an analog and multi-level basis, which is an important requirement for artificial synapses [20,23,32,50,69]. By varying the intensity, duration, and wavelength of the light used to stimulate the device, the STO-based device can replicate many of the functions of biological synapses, including potentiation, depression, and spike-timing-dependent plasticity [51].

9.5 Challenges Toward Practical Implementation:

The use of photoconductive devices based on strontium titanate has many technical challenges that need to be overcome before widespread adoption occurs. Long-term stability, device-to-device reproducibility, and response rates are all challenges that impede the realization of commercial products based on photoconductive materials. While persistent photoconductivity is helpful to memory and neuromorphic applications, it presents a limitation to how fast the device can operate as both a photodetector and a logic device [23,65,68]. Furthermore, the ability to accurately control the oxygen vacancy distribution in the oxide materials is very challenging to do experimentally. Despite these difficulties, advances in epitaxial growth techniques, interface passivation methods, and defect engineering approaches will continue to improve performance and reliability as our understanding of the mechanisms behind photoconductivity in oxides improves; thus enabling the creation of scalable and multifunctional optoelectronic systems.

10. Challenges, Limitations, and Future Outlook:

While there has been considerable development of our knowledge and use of the $SrTiO_3$ (STO)-mediated Photoconductivity, there still exist a number of key challenges, both in concept and practicality, that require resolution prior to the ability of these heterostructures to be produced as reliable and scalable device technologies. As described earlier in this article, many of the unique photoresponses previously addressed arise out of complex interactions between interfacial band alignment, defect chemistry, residual strain, and electronic correlations. Thus, while this interactivity allows for multifunctional behaviors; it also creates a large amount of variability and limits reproducibility when not controlled.



10.1 Control of Oxygen Vacancies and Defect States:

Oxygen vacancies have a large effect on photoconductivity with STO because they can act as electron donors and trapping sites for charge carriers, which allows the STO to have continuous photoconductivity. However, there are a number of issues with controlling the number, arrangement, and stability of vacancies within the deposited layer. Additionally, the conditions under which vacancies form highly depend on the way devices are processed, such as their growth parameters, the type of post-deposition annealing that occurs, and the illumination history that a device has been subjected to. As a result, devices will exhibit considerable variability. Further, it is often very difficult to differentiate between the contributions of intrinsic interfacial electronic reconstruction and defect-affected transport to device performance. Thus, the development of advanced growth processes, such as atomic-layer-controlled epitaxially deposited, and the corresponding increased utilization of in situ spectroscopic measurement techniques will be critical to achieving reproducible interfaces with well-defined defect landscapes. Future studies should place more emphasis on developing quantitatively-defining methods of defect engineering that will provide the ability to predict, tune, and reverse photoconductive characteristics.

10.2 Stability, Fatigue, and Environmental Effects:

Long-term stability also has an effect on the reliability of these devices. Specifically, devices that exhibit persistent photoconductivity, or that exhibit polarization-mediated effects, will experience loss of interface quality due to progressive deterioration of the interface as a result of long-term optical exposure, multiple cycles of electrical use, and environmental exposure. The redistribution of oxygen vacancies will have an effect on the performance of these devices. Long-term stability is an issue that presents reliability limitations; there are additional reliability factors associated with polarization fatigue, imprinting, and depolarization of ferroelectric/STO heterostructures. Potential solutions exist for improving the durability of these devices against fluctuations in ambient conditions, including encapsulation, interface passivation, and protective over-layers, but due to the delicate interface properties that promote increased photoconductivity, these solutions need to be carefully optimized in order to allow for a trade-off of the stability vs. functionality of the devices.

10.3 Speed, Scalability, and Integration Challenges:

Relaxation times are important for creating effective optical memory devices and neuromorphic Devices. However, slow relaxation times limit the ability to use STO-based photoconducting systems in high-speed optoelectronic applications (e.g. LiDAR). Therefore, developing a device architecture that allows for independent control of carrier lifetime, trapping, and transport is critical to obtain fast photoresponse with high photogain. Furthermore, developing new building blocks (e.g. hybrid integration, oxide membrane transfer) and scalable processes (e.g. low-temp growth) will be essential to enable next-generation technologies.

10.4 Outlook and Emerging Directions:

The future of STO mediated photoconductivity will be shaped by many new areas of research. Through the integration of STO with low dimensional materials, such as 2D semiconductors, graphene, and oxide superlattices, new methods for designing interface electronic states with extreme precision and tunability will emerge. In addition, time-resolved optical and spectroscopic techniques are becoming essential tools used to study nonequilibrium carrier dynamics and to separate photoconductive mechanisms. From an application standpoint, photoconductivity combined with ferroelectricity and strong electronic correlations will make STO-based heterostructures attractive platforms for adaptive electronics and neuromorphic computing. The operation of future devices using light as an external control parameter will create possibilities for new functionalities that extend well beyond conventional charge-based operation. There are many challenges ahead. However, the continued development of materials synthesis, interface characterization, and theoretical modeling will allow for the conversion of this exciting phenomenon into a useful basis for the fabrication of next-generation optoelectronic and intelligent devices.

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