Tuning the electrical parameters of p-NiOx based Thin Film Transistors (TFTs) by pulsed laser irradiation

Poreddy Manojreddy¹, Srikanth Itapu²*, Jammalamadaka Krishna Raval³ and Selvendran S⁴

¹ Department of ECE, CVR College of Engineering, Hyderabad, India; manojreddy0359@gmail.com
² School of Electronics Engineering (SENSE), Vellore Institute of Technology (VIT), Vellore, India; srikanth.itapu@rockets.utoledo.edu
³ School of MS, University of Hyderabad, India; 19mbmb12@uohyd.ac.in
⁴ School of Electronics Engineering (SENSE), Vellore Institute of Technology (VIT), Chennai, India; selven-drans@aol.com

* Correspondence: srikanth.itapu@rockets.utoledo.edu

Abstract: We utilized laser irradiation as a potential technique in tuning the electrical performance of NiOx/SiO₂ thin film transistors (TFTs). By optimizing the laser fluence and the number of laser pulses, the TFT performance is evaluated in terms of mobility, threshold voltage, on/off current ratio and subthreshold swing, all of which were derived from the transfer and output characteristics. The 500 laser pulses irradiated NiOx/SiO₂ TFT exhibited an enhanced mobility of 3 cm²/V-s from a value of 1.25 cm²/V-s for as-deposited NiOx/SiO₂ TFT. The laser-irradiated NiOx material likely has a significant concentration of defect gap states, which could also be involved in light absorption processes. Second, and more importantly, the excess energy that the photogenerated charge carriers possess (due to the significant difference between the photon energy and the bandgap of NiOx), combined with the very high light intensity, would result in complex thermal and photo thermal changes thus resulting in an enhanced electrical performance of p-type NiOx/SiO₂ TFT structure.

Keywords: Laser irradiation, p-type NiO, SiO₂ layer, Thin film transistor

1. Introduction

Over the last few years, metal oxide semiconductors have received considerable attention for the applications in thin-film transistors (TFTs) because of their superior physical properties [1]. Extensive research on n-type oxide semiconductors (for example, Indium Gallium Zinc Oxide (InGaZnO), Zinc Oxide (ZnO), and Indium Oxide (In₂O₃)) resulted in industry-specific high-performance oxide TFTs. It is imperative to develop p-type substitutes for the development of next-generation transparent electronics which would enable the development of complementary metal-oxide semiconductor (CMOS) circuits [2], [3]. Few p-type semiconductors such as compounds, Tin Oxide (SnO), Copper Oxide (Cu₂O), and Nickel Oxide (NiO₂), have been demonstrated and incorporated into transistors as the p-type channels. Meanwhile, high performance p-type oxide remains to be a challenging work due to the localized 2p orbitals in the valence band maximum (VBM), the deep VBMs (5–8 eV), and self-compensation by donors [4]. It is well known that stoichiometric deviation alters the electronic structure, and oxygen vacancy causes the formation of sub-gap defects and donor states in many oxides. Therefore, a trade-off between the stoichiometry and the mechanisms employed for defect termination processes are determine the extent of electrical performance of the p-type oxide transistors.

Among various p-type oxide candidates, NiOx is an interesting and promising material due to its superior optical transparency, chemical stability and wide range of applicability vis-à-vis, rectifying diodes [5], p-type Metal Insulator Semiconductor (MIS) structures [6], tin whisker growth mitigation by NiO sublayers [7], etc. The stoichiometric
NiO is a Mott insulator with a conductivity of $10^{-13}$ S/cm, while nonstoichiometric NiO$_x$ is a wide-band-gap p-type semiconductor. The p-type conductivity of NiO$_x$ originates from two positive charge compensation which favors Ni$^{2+}$ vacancies [8]. Several methods have been used for growing NiO films, including sputtering [9-12], e-beam evaporation [13, 14], chemical and plasma-enhanced chemical vapor method [15], sol-gel [16], pulsed laser deposition [17], spray pyrolysis [18, 19]. Sputtering, which is a type of physical vapor deposition technique, is preferred due to its industrial scalability. However, the composition and electrical conductivity of sputtered films are far from equilibrium [20, 21]. Lattice defects are not well-defined in NiO films with high oxygen content [22]. Some studies used working gas and thermal annealing to adjust the film composition and found that the lattice parameter increased with increasing oxygen content, thus resulting in oxygen interstitials as the dominant defects. However, the lattice parameter may not be appropriate to determine the dominant mechanism. On the other hand, the dynamics of interstitials/vacancies created due to laser irradiation are little discussed regarding non-stoichiometric NiO films [23].

Similarly, laser irradiation has been used for modifying intrinsic properties of metallic [24, 25], semiconducting [26–29], superconducting [30], multiferroic [31] and ceramic [32] thin films. In [33], the most frequently used high dielectric material, hafnium oxide (HfO$_x$) was subjected to irradiation by continuous wave laser with wavelength 355nm to analyze the temporal behavior of absorption annealing. In [34], post-deposition annealing of tin oxide (SnO$_x$) thin films by ultra-short laser pulses resulted in a change in refractive index and conductivity of the films. Significant modification in the stoichiometry, desorption of dopant atoms and adsorption of hydrogen atoms from the atmosphere were also observed. Crystallization of amorphous titanium oxide (TiO$_x$) by pulsed laser irradiation using an excimer laser is studied in [35]. Cadmium oxide (CdO) thin films deposited by sol-gel coating method were laser irradiated using a Q-switched Nd:YAG laser operating at its first and second harmonic wavelengths in [36]. An agglomeration of nanoparticles and variation in the bandgap, photoluminescence spectra with laser irradiation were observed. The structural, optical, luminescent and vibrational properties of zinc oxide (ZnO) under the influence of continuous-wave CO$_2$ laser irradiation were studied in [37]. In this work, we explore the effect of ultra-violet (UV) laser irradiation in tuning the properties of NiO thin films, thus enhancing the electrical performance of NiO based TFTs.

In [38], the low-temperature solution-processed p-type nickel oxide thin films along with an aqueous high-k aluminium oxide Al$_2$O$_3$ gate dielectric significantly improved the electrical performance of NiO$_x$ TFT compared to those based on SiO$_2$ dielectric. The hole mobility was reportedly enhanced by 60 times from 0.07 to 4.4 cm$^2$/Vs. Similarly, ink-jet printed p-type NiO TFTs annealed at 280°C in [39], gave the best electrical performance with field-effect mobility of 0.78 cm$^2$/Vs, SS of 1.68 V/dec, on/off current ratio ($I_{on}/I_{off}$) of 5.3 x $10^4$ with a 50nm Al$_2$O$_3$ insulator layer. By optimizing the annealing temperature, precursor concentration, source/drain electrodes, and dielectric material, the authors in [40] successfully achieved p-type NiO TFTs with remarkable mobility of 6.0 cm$^2$/Vs, excellent on/off current modulation ratio of 10$^7$, as well as a good subthreshold swing of 0.13 V/decade at a low processing temperature of 250°C. Hence, from our previous works
we propose the non-contact laser irradiation on sputter-deposited NiOₓ/SiO₂ based TFTs as a potential technique to enhance the electrical parameters by tuning the laser fluence and a number of laser pulses. In this work, the relation between the number of laser pulses to the mobility of NiOₓ, threshold voltage, on/off ratio and subthreshold swing of NiOₓ/SiO₂ TFT device is also studied extensively.

2. Experimental Details

Nickel oxide films were deposited on SiO₂/Si substrate by reactive radio frequency (RF) magnetron sputtering from a 99.99% pure Ni target in an 80:20 oxygen–argon gas mixture at 300°C. We used multiple cleaning steps for our substrate. The cleaning procedure is as follows: wash in cleaning solution (Micro-90), then thoroughly rinse with DI water, followed by an ultra-sonication bath in methanol for 20-25 min, and, finally, ultra-sonication bath in ethanol for 20-25 min. In between these steps, the surfaces are rubbed with a lint-free wipe and blown dry with nitrogen. The thickness of the films was found to be about 100nm using spectroscopic ellipsometry studies. Figure 1 depicts the layered structure of the NiOₓ based TFT. Post-deposition, the TFT device is subjected to Nd:YAG laser irradiation laser operating at its fourth harmonic wavelength λ = 266 nm at room temperature (RT) with optimized laser fluence of 150 mJ/cm² for different number of pulses (Figure 2 (a-d)). The laser fluence is kept below a threshold for any observable physical damage/ablation. The mobility was obtained using a Hall effect measurement setup at room temperature with a magnetic field of 2500 G. The polycrystalline structure of the as-deposited NiOₓ is verified on a Rigaku X-ray diffractometer with Cu Kα radiation (λ = 0.154nm) and a Ni filter.

Figure 1. Layered structure of laser irradiated NiOₓ based TFT (Staggered bottom gate TFT).
3. Results and Discussion

Figure 3. Dependence of number of laser pulses on electrical performance of the proposed TFT

Figure 3(a) represents the relationship between on/off current ratio and the number of laser pulses. The on/off current ratio \( I_{on}/I_{off} \) is usually defined as the ratio of the maximum \( I_{DS} \) to the minimum \( I_{DS} \) (typically in saturation region), which can be extracted from the transfer characteristic curve. If the number of laser pulses increases from 0 to 500, then the ratio value constantly increases to \( 10^5 \).

Figure 3(b) depicts the relationship between mobility and the number of laser pulses. Mobility is a parameter related to the efficiency of carrier transport in the material, which directly affects the maximum \( I_{DS} \) and the operating frequency of devices. Mobility is affected by several scattering mechanisms, including lattice vibrations, ionized impurities, grain boundaries, interface surface roughness, lattice strain and other structural defects, velocity saturation, and electron trapping [41]. Field-effect mobility which is the most widely used parameter to evaluate TFT performance, gradually increases from 1.25 cm\(^2\)/V-s to 3 cm\(^2\)/V-s as the number of laser pulses increases in steps of 100 pulses to 500 pulses.

Figure 3(c) establishes the relationship between the threshold voltage and the number of laser pulses. The threshold voltage \( V_{TH} \) is the value of \( V_{GS} \) when the accumulation layer or conductive channel formed near the dielectric layer/active layer interface in TFTs. Depending on the values of \( V_{TH} \) being negative or positive, the p-type TFT devices typically operate in
enhancement or depletion modes respectively. As the number of laser pulses increases from 0 to 500, then the value of threshold voltage increases slightly more than 12 V.

The subthreshold swing (SS) is an important parameter that indicates the switching efficiency of a transistor. The SS is directly related to the quality of the dielectric/semiconductor interface and defined as the inverse of the maximum slope of the transfer characteristic and reflected by the $V_{GS}$ needed to increase the $I_{DS}$ by one decade in the sub-threshold region. When the SS value is low, then the operation speed is high, and the power consumption is also low. As the number of laser pulses increases from 0 to 500, then the value of SS decreases from 3.8 to 0.65 V/decade (Figure 3(d)).

Furthermore, the associated ($I_{DS}$) and $I_{GS}$ as a function of the $V_{GS}$ were shown in Figure 4(a, b). It was found that the saturation drain-source current and the gate leakage current were $-40 \mu A$ and $-8 \mu A$, respectively, when the p-type NiO TFTs operated at a $V_{DS}$ of $-10V$ and a $V_{GS}$ of $-9V$. The associated on-to-off current ratio was $10^5$. The associated threshold voltage and subthreshold swing were $-4V$ and $0.56V$/decade, respectively.

![Transfer Characteristics](image)

**Figure 4.** Drain-source current and transconductance as a function of gate-source voltage of p-type NiO thin-film transistor.

The output characteristics of p-type NiO based TFT is divided into two main operating regions depending on the value of $V_{DS}$: linear and saturation regions. In linear region, $V_{GS}$ controls the channel resistance thus accumulating charges uniformly in the channel. In saturation region, for a constant $V_{GS}$, $I_{DS}$ is constant, which suggests lack of channel region due to depletion of charges in the accumulation layer. For the 500 pulses laser-irradiated NiO/SiO$_2$ TFT, the output characteristics are shown in Figure 5.
Figure 5. Drain source current- drain source voltage characteristics of the NiO TFT.

At constant $V_{GS}$ of 0V, when voltage $V_{DS}$ increases from 0V to 20V then the value of current $I_{DS}$ increases from 0µA to 1.6µA. At constant $V_{GS}$ of -3V, when voltage $V_{DS}$ increases from 0V to 20V then the value of current $I_{DS}$ increases from 0µA to µA. At constant $V_{GS}$ of -6V, when voltage $V_{DS}$ increases from 0V to 7.5V then the value of current $I_{DS}$ increases from 0µA to 15µA and remains constant up to 20V. Again, at constant $V_{GS}$ of -9V when voltage $V_{DS}$ increases from 0V to 10V then the value of current $I_{DS}$ increases from 0µA to 40µA and remains constant up to 20V.

5. Conclusions

In this work, we studied the effects of laser irradiation in enhancing the electrical performance of p-type NiO TFT with SiO$_2$ as high-k dielectric layer. The mobility increased from 1.25 cm$^2$/V-s for as-deposited NiO thin film to 3 cm$^2$/V-s for 500 laser pulse irradiated sample. Similar enhancements were observed for laser irradiated sample in terms of the threshold voltage, subthreshold swing and the on/off current ratio. The plausible mechanism responsible for the reported phenomenon was that the excess energy, photogenerated charge carriers possess (due to the significant difference between the photon energy and the bandgap of NiO), combined with the very high light intensity, results in a complex thermal and photo thermal changes, thus enhancing the electrical performance of the TFT.

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