# Characteristics of Top-Gate Thin-Film Transistors Fabricated on Nitrogen-Implanted Polysilicon Films

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*Abstract*—**The electrical characteristics of top-gate thin-film transistors (TFT's) fabricated on the nitrogen-implanted polysilicon of the doses ranging from $2 \times 10^{12}$–$2 \times 10^{14}$ ions/cm$^2$ were investigated in this work. The experimental results showed that nitrogen implanted into polysilicon followed by an 850°C 1 h annealing step had some passivation effect and this effect was much enhanced by a following $H_2$-plasma treatment. The threshold voltages, subthreshold swings, ON-OFF current ratios, and field effect mobilities of both n-channel and p-channel TFT's were all improved. Moreover, the hot-carrier reliability was also improved. A donor effect of the nitrogen in polysilicon was also found which affected the overall passivation effect on the p-channel TFT's.**

## I. Introduction

The incorporation of nitrogen into the gate-dielectrics of MOS devices by different processes has been widely investigated to improve the reliability of MOSFET's [1]–[6]. The improved reliability is mainly due to the fact that most of the incorporated nitrogen can pile up at the gate-$SiO_2$/Si interface to make the interface more robust and then to improve the hot-carrier immunity. Moreover, the incorporation of nitrogen can also suppress boron penetration from the $p^+$-polysilicon gate of p-MOSFET's due to the formation of gate oxynitrides. To optimize the gate-oxynitride quality, the process of $NH_3$-nitrided oxides followed by proper reoxidation has been extensively studied [1], [2]. Recently, $N_2O$-annealed oxides have also become a promising alternative due to its process simplicity [3], [4]. In addition, nitrogen ion implantation is another alternative to suppress the boron penetration and hot-carrier degradation of MOSFET's [5], [6].

However, little attention has been paid to study the effects of incorporating nitrogen into polysilicon thin-film transistors (TFT's). Recently, it was reported that the polysilicon TFT with a proper low-pressure $NH_3$ annealing treatment has a better effect in responding to the $H_2$-plasma passivation. The pile-up nitrogen at the interface could form oxynitride to promote the $H_2$-plasma passivation [7]. Another study also showed that, compared to the control device without nitrogen implantation, the nitrogen-implanted polysilicon TFT had the better performance [8]. In this work, the electrical characteristics of the TFT's fabricated on the nitrogen-implanted polysilicon films were described and discussed in more detail.

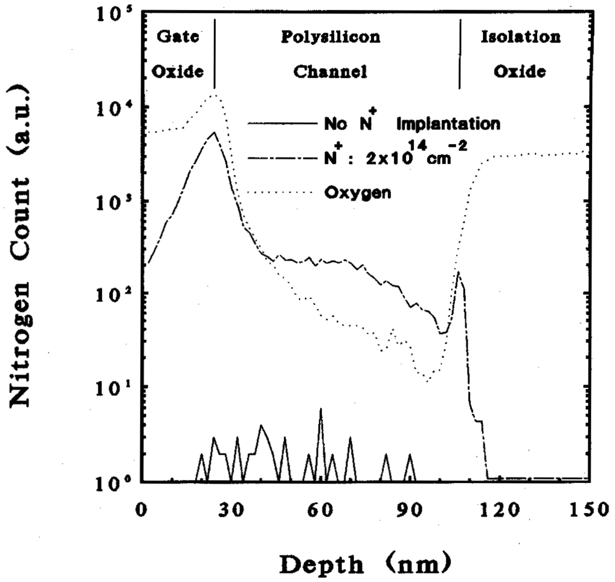

Fig. 1. The oxygen and nitrogen SIMS profiles for the devices implanted with $2 \times 10^{14}$ N/cm$^2$ and without nitrogen implantation.

## II. Experimental Procedures

The polysilicon TFT's studied in this work were fabricated as follows. Undoped amorphous silicon films of 100 nm thickness were initially deposited on thermally oxidized silicon wafers by an LPCVD system at 550°C and then crystallized at 600°C for 24 h to form the polysilicon films. Doses of nitrogen varying from $2 \times 10^{12}$ to $2 \times 10^{14}$ cm$^{-2}$ were implanted at 25 keV through an oxide into the polysilicon films and then annealed in an $N_2$ ambient at 850°C for 1 hr. After that step the oxide was removed and the active island was defined; subsequently, about 29 nm of gate oxide was grown in dry $O_2$ at 850°C. Another 300 nm polysilicon film was then deposited by LPCVD and patterned by plasma etching to be the gate electrode. Source, drain, and gate electrodes were doped by the self-aligned phosphorous and boron implantations of a dose of $5 \times 10^{15}$ cm$^{-2}$ for the n-channel and p-channel devices, respectively. The dopants were activated at 850°C for 30 min in an $N_2$ gas. Some of the samples were subjected to the $H_2/N_2$ plasma treatment in a commercial plasma-enhanced

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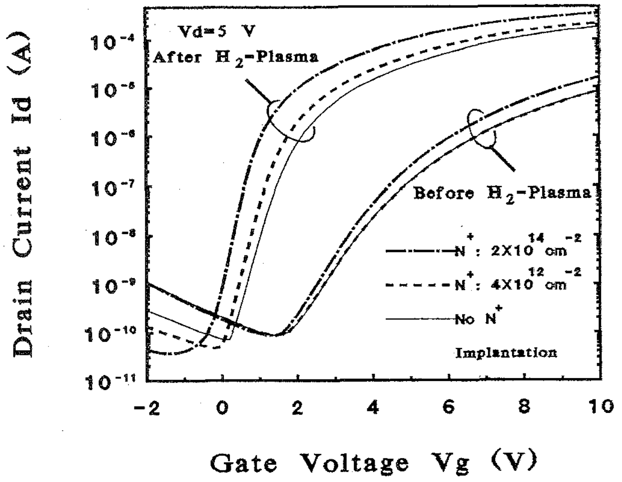
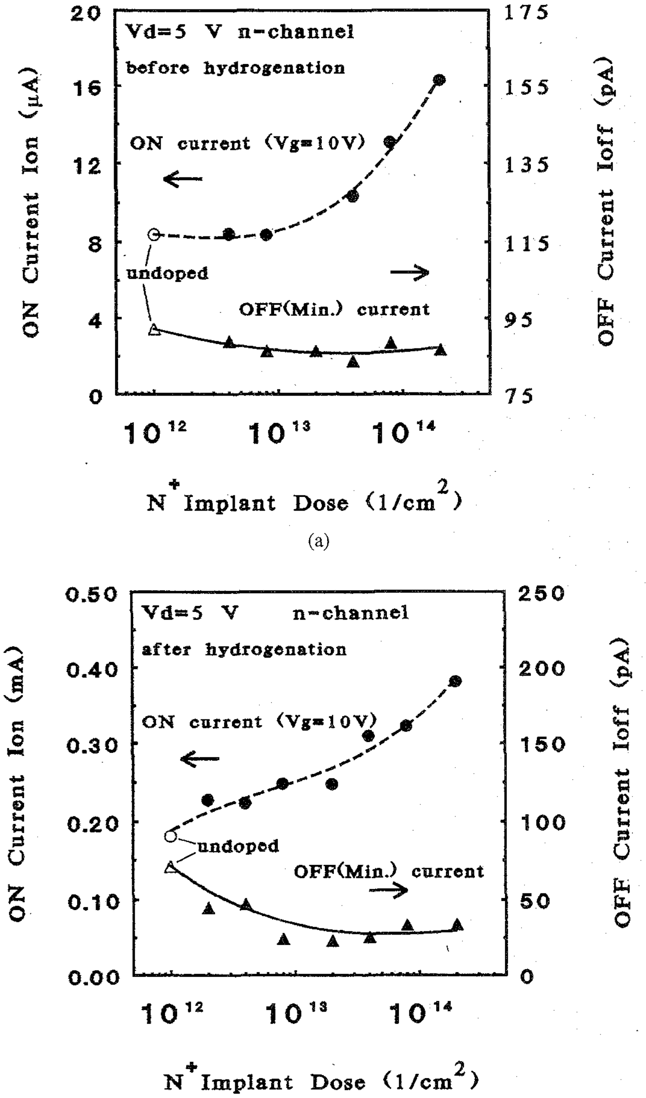


Fig. 2. $I_d$-$V_g$ characteristics of the TFT's with respect to different nitrogen doses before and after the $H_2$-plasma treatments. ($W/L = 40\,\mu$m/10 $\mu$m).



(a)

(b)

Fig. 3. The variations of ON and OFF currents of (a) unhydrogenated and (b) hydrogenated n-channel devices as a function of the implanted nitrogen dose. The OFF current is defined at the minimum drain-current level. ($W/L = 40\,\mu$m/10 $\mu$m).

chemical vapor deposition (PECVD) system at 300°C for 1 h. All devices were then capped with a 360 nm PECVD $SiO_2$. Finally, after contact holes were opened, Al was deposited and patterned. During the above process, control devices without the nitrogen implantation but with an 850°C 1 h $N_2$-annealing were also fabricated for comparison. The total heat treatment time for every sample, without or with nitrogen implantation, was the same.

## III. RESULTS AND DISCUSSIONS

### *A. The Passivation Effect of Nitrogen*

Fig. 1 shows the SIMS profiles of oxygen and nitrogen after the dopant-activation annealing and gate-oxide growth for the devices implanted with nitrogen dose of $2 \times 10^{14}$ $cm^{-2}$ and without nitrogen implantation. It is seen that for the sample implanted with $2 \times 10^{14}$ N/$cm^2$, nitrogen not only piled up at the gate-oxide/polysilicon interface but also diffused deeply into the bulk of the polysilicon and some of it piled up at the polysilicon/isolation-oxide interface. From the $C$–$V$ measurement, we did not find any obvious increase in the gate-dielectric capacitance as the dose was increased. However, from this SIMS data, it can be speculated that a thin gate oxynitride layer could have formed on the surface of the channel.

Fig. 2 shows the $I_d$-$V_g$ characteristics of the unhydrogenated and hydrogenated n-channel TFT's with $4 \times 10^{12}$ $cm^{-2}$, $2 \times 10^{14}$ $cm^{-2}$ nitrogen implantations and without nitrogen implantation, respectively. Fig. 3(a) and (b) plots the ON/OFF currents as a function of nitrogen dose for the n-channel devices before and after $H_2$-plasma treatments, respectively. It is seen that as nitrogen dose was increased to $4 \times 10^{13}$ $cm^{-2}$, the $I$–$V$ characteristic was improved even without hydrogenation applied. After hydrogenation, the devices without and with nitrogen implantation were all remarkably improved and the nitrogen-implanted devices were more improved. The greater the nitrogen implantation dose, the more improvement on the ON/OFF ratio was obtained, especially for the hydrogenated devices. Fig. 4 shows the activation energies of the drain currents as a function of the gate voltage at $V_d = 0.1$ V corresponding to the devices in Fig. 2. For this figure, the activation energies were calculated from the Arrhenius plots of the drain currents measured from 30°C to 120°C. It can be seen that, before the $H_2$-plasma treatment, the $2 \times 10^{14}$ $cm^{-2}$ nitrogen implantation effectively reduced the activation energy. After the $H_2$-plasma treatment, all the three curves were improved and the device with a higher nitrogen dose was more improved. The value of the activation energy reflects the carrier transport barrier of the grain boundary within the polysilicon channel. The lower the activation energy is, the lower the effective trap-state density is. This indicates that nitrogen itself has some passivation effect on the trap states

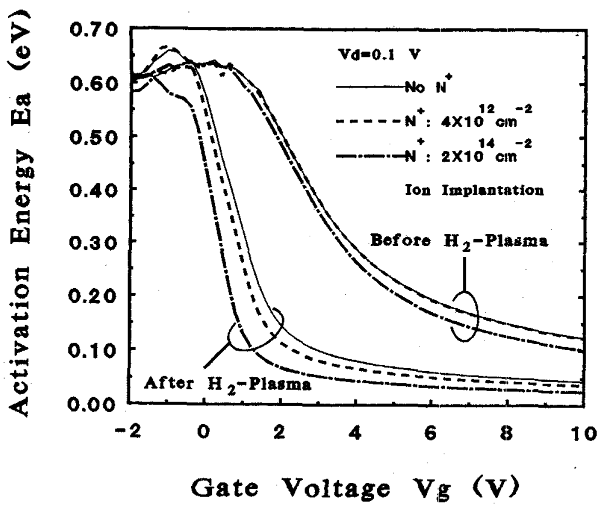
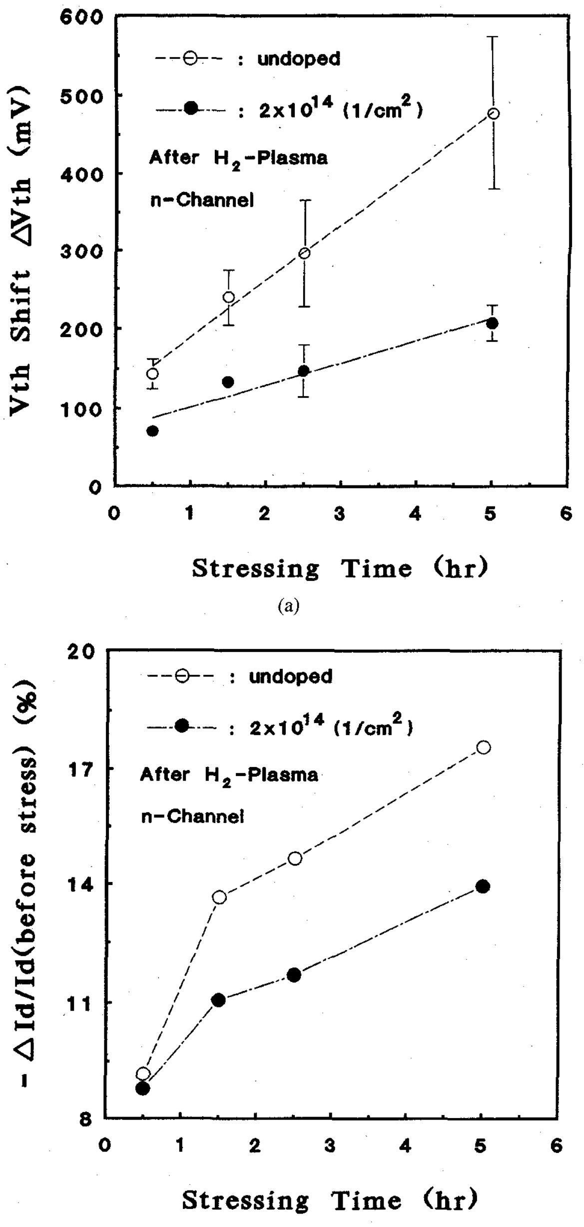


Fig. 4. The drain-current activation energies of the unhydrogenated and hydrogenated TFT's with two different nitrogen doses.



(a)

(b)

Fig. 5. (a) The threshold voltage shift and (b) the drain current reduction (measured at $V_d = 5$ V and $V_g = 10$ V) for the nitrogen-implanted and unimplanted n-channel devices after they were stressed at $V_d = 20$ V and $V_g = 5$ V for different times. ($W/L = 40\,\mu$m/5 $\mu$m).

of TFT's, and in addition, it could assist the passivation effect of the $H_2$-plasma [7]. The effective trap-states are composed of the interface trap-states and the bulk trap-states, and the former are generally smaller than the latter before plasma hydrogenation [9]. In Fig. 1, it is noted that the implanted nitrogen not only piled up at the poly-Si/$SiO_2$ interface but also distributed themselves in the bulk of the polysilicon channel. Hence, in Fig. 4, for the curves before the $H_2$-plasma treatment, the improvement of the device implanted with $2 \times 10^{14}$ N/cm$^2$ might be mainly due to the reduction of the bulk trap-states, and the reduction was possibly caused by the incorporated nitrogen by implantation which was followed by an 850°C $N_2$-annealing. For the device implanted with $4 \times 10^{12}$ N/cm$^2$, the improvement was minimal since most of the nitrogen atoms piled up at the $SiO_2$/polysilicon interface and passivated only the interface trap-states. After the $H_2$-plasma treatment, the greater improvement on the device implanted with $4 \times 10^{12}$ N/cm$^2$ was seen, as compared to the device without nitrogen implantation. This implies that the trap states left after the $H_2$-plasma treatment were mostly the interface trap states, and the nitrogen pile-up at the interface could passivate these trap states beforehand to promote the $H_2$-plasma passivation. The passivation effect of nitrogen on the interface defects, such as Si dangling bonds and/or strained bonds, was also reported in MOSFET cases [10], [11]. However, before the $H_2$-plasma treatment, the OFF-state currents were not obviously improved even for the device implanted with the high nitrogen dose. It was probably due to effects of processing-induced defects, such as those caused by ion implantation, on the source/drain junctions [12] since the OFF-state currents were mainly caused by the defects of drain p-n junction. From the data in Figs. 2 and 3, these defects could be passivated by the $H_2$-plasma treatment.

The hot carrier reliability on the hydrogenated polysilicon TFT's without and with the nitrogen implantation was also investigated. Fig. 5(a) and (b) shows the threshold-voltage shifts and the drain-current reductions, respectively, for the devices without and with the $2 \times 10^{14}$ cm$^{-2}$ nitrogen implantation after they were stressed at $V_d = 20$ V and $V_g = 5$ V for different times. The threshold-voltage shift was defined at $V_d = 0.1$ V and $I_d = 800$ nA and the drain-current reduction was measured at $V_d = 5$ V and $V_g = 10$ V for $W/L = 40\,\mu$m/5 $\mu$m. It is seen that the threshold-voltage variation and the drain-current degradation were significantly suppressed for the hydrogenated devices with the nitrogen implantation. This might be due to that stronger Si-N and N-H bonds, instead of some weaker Si-H bonds [13], [14], were formed for the nitrogen-implanted device during the

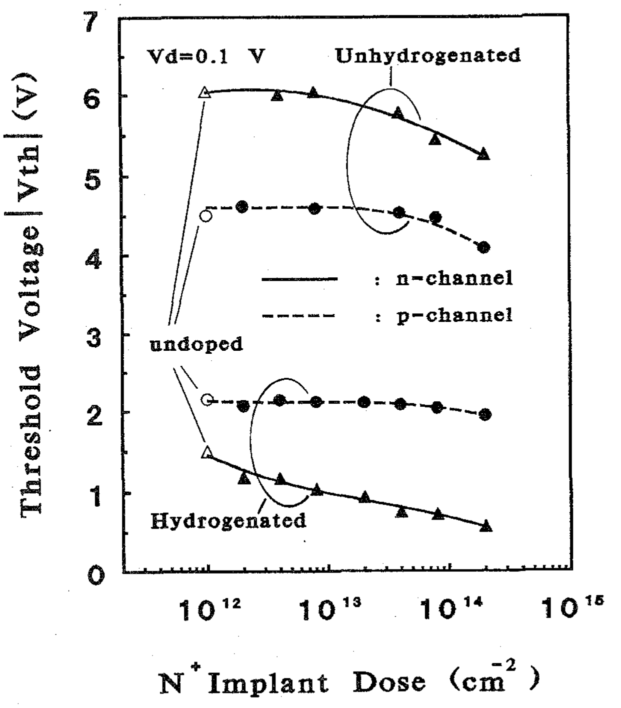


Fig. 6. Dependence of the threshold voltage on the implanted nitrogen dose for the unhydrogenated and hydrogenated n-channel and p-channel devices, respectively. The undoped devices are denoted by the open dots. ($W/L$ = 40 $\mu$m/10 $\mu$m).

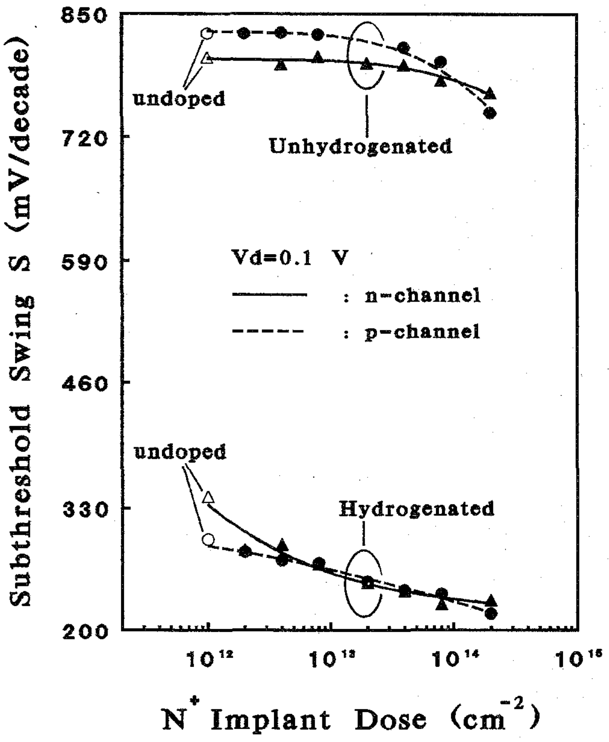


Fig. 7. Dependence of the subthreshold swing on the implanted nitrogen dose for unhydrogenated and hydrogenated n-channel and p-channel devices. The undoped devices are denoted by the open dots. ($W/L$ = 40 $\mu$m/10 $\mu$m).

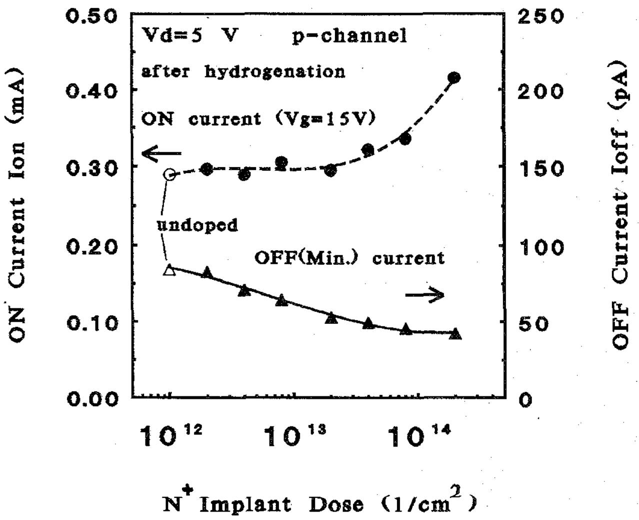
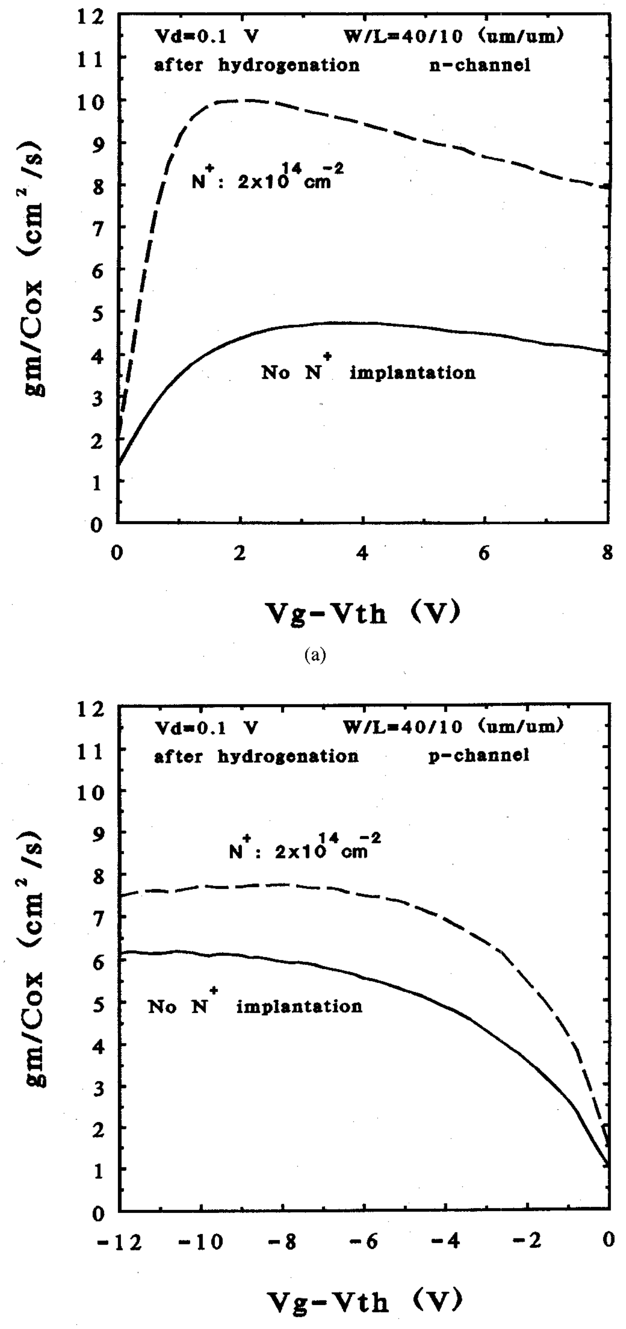


Fig. 8. The variations of ON and OFF currents of p-channel devices after the $H_2$-plasma treatment as a function of the nitrogen dose. ($W/L$ = 40 $\mu$m/10 $\mu$m).

$H_2$-plasma treatment, and the incorporated nitrogen atoms strengthened the oxide/polysilicon interface.

### *B. The Donor Effect of Nitrogen*

Fig. 6 shows the threshold voltages as a function of nitrogen dose for the n-channel and p-channel devices before and after $H_2$-plasma treatments, respectively. The threshold voltage was defined at a fixed normalized drain current, $I_d \times (L/W) = 10$ nA. There were larger threshold-voltage shift on the n-channel device than on the p-channel device. Also, the variation of the threshold voltage with respect to the nitrogen implantation dose for the n-channel device was larger than those for the p-channel device. After the $H_2$-plasma treatment, the above phenomenon was much enhanced. One possible explanation for this result could be that, similar to the case of nitrogen in single-crystal silicon [15], a donor layer was created for the polycrystalline-silicon channel. For the n-channel devices, the combined passivation effects of $H_2$-plasma and nitrogen implantation and the donor effect of the implanted nitrogen made the threshold voltages shift significantly toward the negative end. Moreover, as the implantation dose increased, these effects also increased and this made the shifts larger. For the p-channel devices, the donor effect of nitrogen was in opposite to the passivation effects of $H_2$-plasma and nitrogen implantation. This made the threshold voltage shifts smaller and more insensitive to the nitrogen implantation dose. The above explanation can also be supported by Fig. 7, where the subthreshold swings of the n-channel and p-channel devices, before and after the $H_2$-plasma passivations, with respect to the nitrogen implantation dose were plotted respectively. Before the $H_2$-plasma, the passivation effect was not significant until the nitrogen implantation dose was higher than $2 \times 10^{13}$ $cm^{-2}$ for both the n-channel and p-channel devices. It means that before hydrogenation, the dose of implanted nitrogen must be high enough to passivate the defects. However, after the $H_2$-plasma treatment, the subthreshold swings were heavy *functions* of the nitrogen implantation dose. That is, the more the nitrogen implantation dose, the more the passivation effect and consequently, the smaller subthreshold swing. The smaller subthreshold swing reflects the lower trap-states. It is known that the threshold-voltage variation is attributed to the trap-states as well as the substrate doping level. According to Fig. 7, we can find that the reduction of the trap-states for the n-channel devices is not superior than that for the p-channel devices. Therefore, it is believed that the donor effect of nitrogen is the dominant reason for the larger threshold-voltage shifts of the n-channel devices. The donor effect of nitrogen can be also observed in Fig. 8, where the ON and OFF currents of the p-channel devices after the $H_2$-plasma were plotted. Comparing Fig. 8 with Fig. 3(b), we can find that the OFF-current curves were similar for both the n-channel and p-channel devices but the ON-current curves were very different. The OFF-current decreased with the increased nitrogen implantation dose. This was dominantly due to the passivation effect of the implanted nitrogen. For the ON-curves, it increased with the nitrogen implantation dose for the n-channel devices but was independent of the nitrogen implantation dose until the dose reached $4 \times 10^{13}$ cm$^{-2}$ for the p-channel devices. This was because for the implanted nitrogen dose below $4 \times 10^{13}$ cm$^{-2}$, the nitrogen donor effect compensated the nitrogen passivation effect. As the nitrogen dose was above $4 \times 10^{13}$ cm$^{-2}$, the nitrogen donor effect essentially saturated [16] and the nitrogen passivation effect became dominant and, as a result, the ON current increased. In MOSFET cases, the nitrogen donor effect was also considered to be a possible mechanism to explain the difference in the performance of n- and p-channel devices [17], [18].



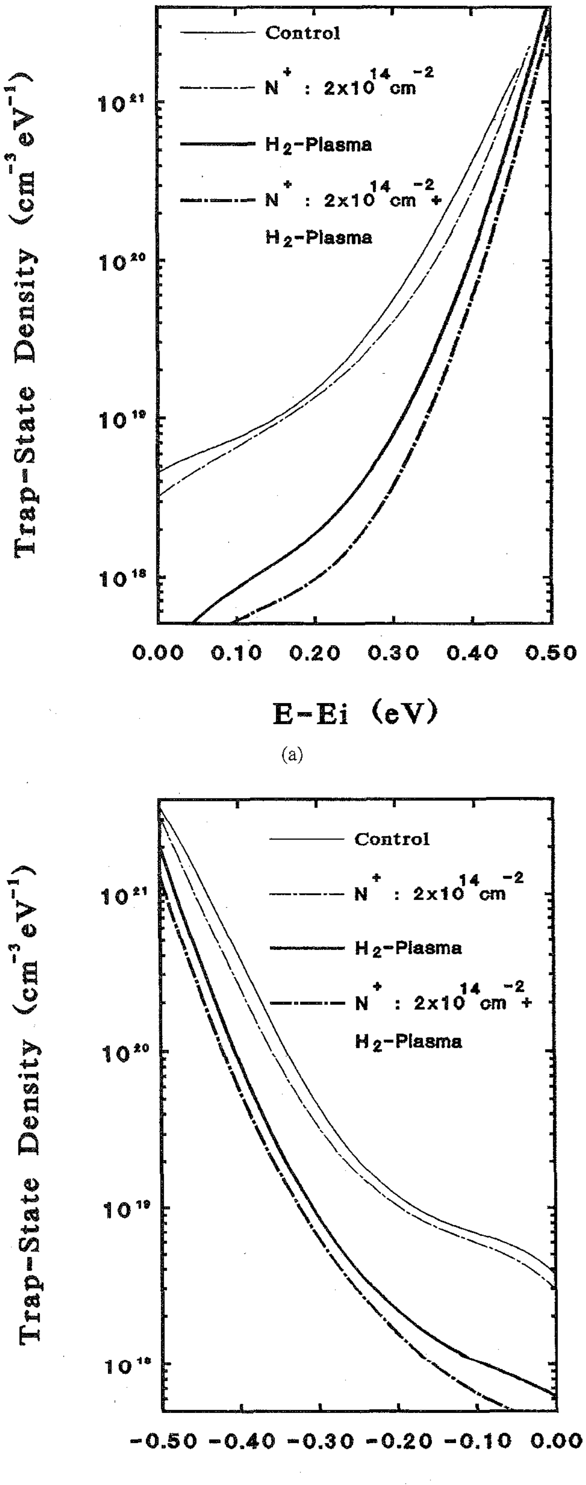
(a)

(b)

Fig. 9. Dependence of the Cox-normalized transconductance on the gate bias for the (a) n-channel, and (b) p-channel TFT's without and with $2 \times 10^{14}$ cm$^{-2}$ nitrogen implantations.

### *C. Other Characteristics*

Tables I and II summarize the values of electrical parameters of the TFT's with the $2 \times 10^{14}$ cm$^{-2}$ nitrogen implantation only, with the $H_2$-plasma treatment only, and with both the $2 \times 10^{14}$ cm$^{-2}$ nitrogen implantation and the $H_2$-plasma treatment, and the control device without any treatment for both n-channel and p-channel devices, respectively. It is seen that the device with both the nitrogen-implantation and the $H_2$-plasma treatment had the best electrical performance. The improved characteristics were comparable to that of the fluorine-implanted devices [19]. For the nitrogen-implanted then $H_2$-plasma treated devices and the $H_2$-plasma-treated devices, the field effect mobilities, defined by $(g_m/C_i) \cdot (W/L) \cdot V_d$ where $g_m = \partial I_d/\partial V_g$, were plotted in Fig. 9(a) and (b) for the n-channel and p-channel devices, respectively. It is seen that for the nitrogen-implanted devices, the field effect mobility increased for both the n-channel and p-channel devices. Fig. 10(a) and (b) shows the distributions of the forbidden band effective trap-state densities, extracted from the relation of $I_d$–$V_g$ at $V_d = 0.1$ V [20] for all the devices of Tables I and II, respectively. It is seen that both the tail-states and deep-states are passivated by the nitrogen implantation for the devices without and with an $H_2$-plasma treatment. According to our experimental results, for the range of the nitrogen dose of $2 \times 10^{12}$ to $2 \times 10^{14}$ cm$^{-2}$, the higher the nitrogen dose, the more improvement was obtained on the trap-state density for both the n-channel and p-channel devices. It is known that in the MOSFET cases, the high concentration of nitrogen at the $SiO_2$/Si interface, incorporated by either heavy nitridation [2] or nitrogen implantation [6], would cause a higher interface state density or a lower peak transconductance. However, in this study on TFT, the nitrogen incorporated at the $SiO_2$/poly-Si interface did not degrade the interface state and $g_m$ of the TFT.



(a)

(b)

Fig. 10. (a)–(b) The derived distributions of the effective trap-state densities for the devices of Tables I and II at $V_d = 0.1$ V.

TABLE I
THE VALUES OF THE SUBTHRESHOLD SWING ($S$), THE THRESHOLD VOLTAGE ($V_{th}$), THE FIELD EFFECT MOBILITY ($\mu$, PEAK VALUE IN THE GATE VOLTAGE RANGING FROM 0–10 V), AND THE MINIMUM DRAIN CURRENT ($I_{\min}$) OF THE POLYSILICON TFT'S WITH THE $2 \times 10^{14}$ cm$^{-2}$ NITROGEN IMPLANTATION ONLY, WITH THE H$_2$-PLASMA TREATMENT ONLY, AND WITH BOTH THE $2 \times 10^{14}$ cm$^{-2}$ NITROGEN IMPLANTATION AND THE H$_2$-PLASMA TREATMENT, AND THE CONTROL DEVICE WITHOUT ANY TREATMENT FOR THE n-CHANNEL DEVICES

| Conditions | S (mV/dec) | Vth (V) | μ (cm²/Vsec) | Imin (pA) |
|---|---|---|---|---|
| | at Vd=0.1 V | | | at Vd=5 V |
| Control | 803 | 6.0 | 2.3 | 92.2 |
| N$^{+}$:2x10$^{14}$cm$^{-2}$ | 766 | 5.3 | 4.4 | 86.8 |
| H$_2$-plasma | 342 | 1.5 | 12.0 | 71.4 |
| N$^{+}$:2x10$^{14}$cm$^{-2}$<br>+H$_2$-plasma | 232 | 0.6 | 25.0 | 34.0 |

W/L = 40 μm / 10 μm

TABLE II
THE VALUES OF THE SUBTHRESHOLD SWING ($S$), THE THRESHOLD VOLTAGE ($V_{th}$), THE FIELD EFFECT MOBILITY ($\mu$, PEAK VALUE IN THE GATE VOLTAGE RANGING FROM 0–10 V), AND THE MINIMUM DRAIN CURRENT ($I_{\min}$) OF THE POLYSILICON TFT'S WITH THE $2 \times 10^{14}$ cm$^{-2}$ NITROGEN IMPLANTATION ONLY, WITH THE H$_2$-PLASMA TREATMENT ONLY, AND WITH BOTH THE $2 \times 10^{14}$ cm$^{-2}$ NITROGEN IMPLANTATION AND THE H$_2$-PLASMA TREATMENT, AND THE CONTROL DEVICE WITHOUT ANY TREATMENT FOR THE p-CHANNEL DEVICES

| Conditions | S (mV/dec) | Vth (V) | μ (cm²/Vsec) | Imin (pA) |
|---|---|---|---|---|
| | at Vd=0.1 V | | | at Vd=5 V |
| Control | 829 | -4.5 | 4.1 | -222.4 |
| N$^{+}$:2x10$^{14}$cm$^{-2}$ | 750 | -4.1 | 7.1 | -170.7 |
| H$_2$-plasma | 297 | -2.2 | 14.9 | -84.3 |
| N$^{+}$:2x10$^{14}$cm$^{-2}$<br>+H$_2$-plasma | 218 | -1.9 | 19.3 | -42.3 |

W/L = 40 μm / 10 μm

## IV. CONCLUSION

In conclusion, from the above study, nitrogen implantation combined with the H$_2$-plasma treatment is a choice to effectively improve the electrical characteristics of the n-channel and p-channel polysilicon TFT's. Experimental results have shown that all the subthreshold swings, threshold voltages, ON/OFF current ratios, field effect mobilities, and trap-state densities were improved by using this technique. In addition, the implanted nitrogen can also improve the reliability of the poly-Si TFT's. The nitrogen implantation followed by an 850°C-1 h N$_2$-annealing has a passivation effect. When it is combined with the H$_2$-plasma passivation, the total passivation effect further enhances the device performance. For the p-channel device, nitrogen is believed to have a donor effect, which makes the improvement of the electrical characteristics not as effective as that of the n-channel device.

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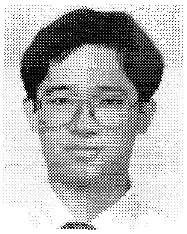

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**Tan Fu Lei**, for a photograph and biography, see p. 1246 of the July issue of this TRANSACTIONS.

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