Hydrogenation of Polysilicon Thin-Film Transistor in a Planar Inductive H_2/Ar Discharge

Ching-Fa Yeh, Tai-Ju Chen, Chung Liu, Jon T. Gudmundsson, *Member, IEEE,*
and Michael A. Lieberman, *Fellow, IEEE*

Abstract—**A planar inductive discharge is used to hydrogenate polysilicon thin-film transistors (poly-Si TFT's). Experimental results indicate that inductive discharges operate at higher plasma densities, thereby capable of shortening the hydrogenation time. In addition, to promote the ionization of hydrogen, Ar gas is also introduced to H_2 plasma during hydrogenation. Furthermore, we discuss the mechanism of Ar enhanced hydrogenation and the characteristics of H_2/Ar mixed plasma. Moreover, the post-hydrogenation anneal is utilized to further enhance passivation efficiency and improve the reliability of poly-Si TFT's.**

Index Terms— **Hydrogenation, inductively coupled plasma, thin-film transistor.**

I. INTRODUCTION

POLYSILICON thin-film transistors (poly-Si TFT's) have received increasing interest owing to their applications in active-matrix liquid-crystal displays (AMLCD's) and static random-access memories (SRAM's). However, grain boundary and intragranular defects in poly-Si films heavily influence TFT performance. Previous studies have demonstrated that hydrogenation is highly effective in reducing these defects. Several techniques have been utilized to perform hydrogenation, including parallel-plate plasma reactors [1] and electron cyclotron resonance (ECR) plasma reactors [2]. During hydrogenation, the rate of hydrogen introduced into the device surface profoundly influences processing time. This rate depends strongly on the ion density in plasma. To shorten hydrogenation time, we apply an inductively coupled plasma (ICP) [3] source to create the high-density hydrogen plasma. ICP has been shown to have a higher plasma density than conventional parallel-plate and ECR discharges [4]. To impel the ionization of hydrogen, Ar gas is introduced into the hydrogen plasma during hydrogenation.

Conventional co-planar N-channel poly-Si TFT's were prepared. The 100-nm-thick LPCVD a-Si layer was recrystallized at 600 °C for 24 h. The 17 nm-thick gate oxide was then grown by liquid-phase deposition [5]. After poly-Si gates were formed, the source/drain and the gate regions were doped by phosphorus ion implantation (5×10^{15} cm^{-2}, 40 KeV). Next, dopant activation was performed at 600 °C for 24 h. The 500 nm-thick interlayer was then deposited using the PECVD method. Aluminum electrodes were formed and sintered at 400 °C for 30 min in N_2 gas. Finally, hydrogenation was performed in an ICP reactor at 50 mTorr and 600 W at 13.56 MHz for 20 min. During plasma exposure, the substrate bias was floating, and no heater was applied to the substrate holder. However, owing to the bombardment of ions and electrons, the substrate temperature rose after starting the plasma and reached an equilibrium temperature of 295 °C within 350 s. For H_2/Ar mixed plasma, the fractional Ar pressure was 0.3. Ion species presented in the plasma were analyzed using a quadrupole mass spectrometer. Detail description of the planar inductive discharge is given elsewhere [3].

Fig. 1 depicts the transfer characteristics of TFT's before and after (a) H_2 and (b) H_2/Ar hydrogenation. For TFT's after H_2 treatment, the improvement is small. This observation implies that pure H_2 plasma can not effectively provide sufficient neutral or ionized atomic hydrogen (H or H^+) for passivation. To provide sufficient H or H^+ for hydrogenation, molecular hydrogen must be impelled to dissociate or ionize initially. Hence, to enhance ionization (Penning effect) to the plasma, we add Ar gas to the plasma. The TFT characteristics are improved after H_2/Ar treatment, resulting in a threshold voltage (V_{th}) of 2.3 V, a subthreshold swing (S.S.) of 0.33 V/dec, an ON-current (I_{on}) of 434 μA and a field-effect mobility (μ_{FE}) of 28.3 cm^2/V · s, compare to V_{th} of 4.2 V, a S.S. of 0.76 V/dec, an I_{on} of 263 μA and a μ_{FE} of 22.3 cm^2/V · s in a control wafer. This finding suggests that the trap states in the channel have been effectively passivated by H and H^+. Such passivation can be confirmed by the reduction of trap-state density (N_t) from 2.62×10^{13} cm^{-2} to 1.16×10^{13} cm^{-2} after H_2/Ar hydrogenation.

Exactly why H_2 can be more effectively ionized in H_2/Ar plasma than in pure H_2 plasma under the same ICP conditions requires a closer examination. In general, the predominant ion species in hydrogen plasma at 50 mTorr are H_2^+ and H_3^+ [6]. In pure H_2 plasma, the generation efficiency of H_2^+ is inadequate due to the small ionization cross-section of H_2. However, according to our results, adding Ar gas into H_2 plasma can effectively enhance the ionization of H_2. To excite the Ar atom to a metastable state Ar* in electron collision requires 11.6 eV, whereas to ionize H_2 to H_2^+ requires 15.9 eV. The reaction $Ar^* + H_2 \rightarrow H_2^+ + Ar + e^-$ then promotes the formation of hydrogen ions (Penning effect). After H_2^+ is generated, some

---

Manuscript received March 24, 1998; revised December 22, 1998. This work was supported by the National Science Council of the Republic of China under Contract NSC 87-2215-E-009-048.

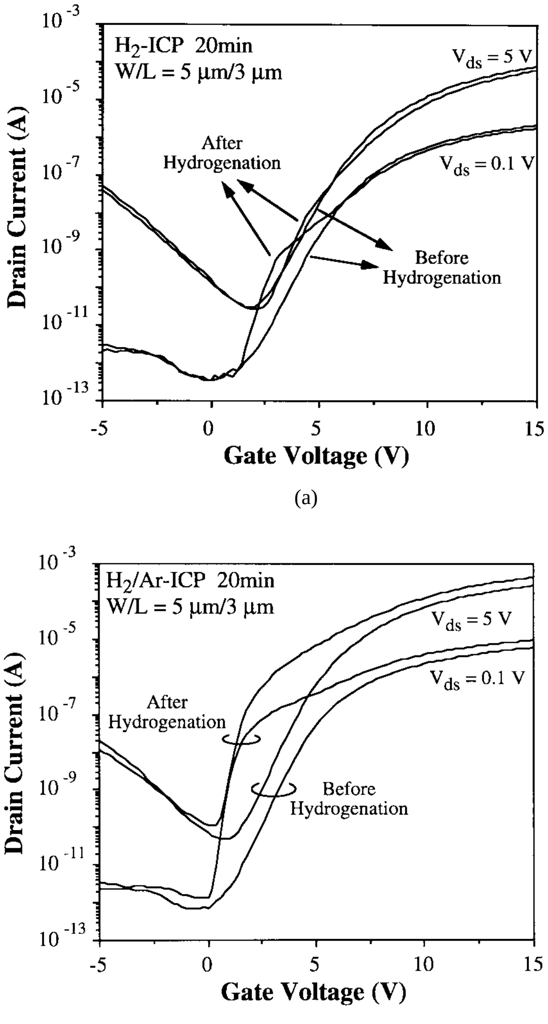
C.-F. Yeh, T.-J. Chen, and C. Liu are with the Department of Electronics Engineering and Institute of Electronics, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C.

J. T. Gudmundsson is with the Science Institute, University of Iceland, IS-107 Reykjavik, Iceland.

M. A. Lieberman is with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA.

Publisher Item Identifier S 0741-3106(99)04414-6.

0741–3106/99$10.00 © 1999 IEEE



(a)

(b)

Fig. 1. Transfer characteristics at $V_{\rm ds} = 0.1$ and 5 V for poly-Si TFT's before and after (a) pure H_2 and (b) H_2/Ar ICP hydrogenation for 20 min.

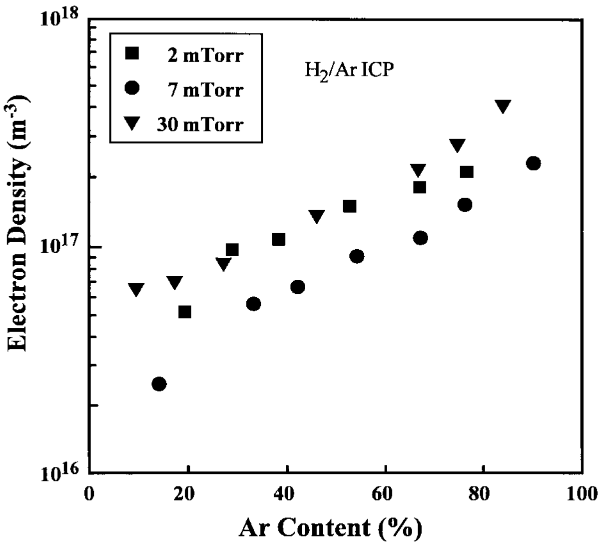


Fig. 2. Electron density as a function of fractional argon pressure in H_2/Ar plasma under different operating pressures.

H_2^+ chemically reacts with H_2 to generate H_3^+ [6], [7]. Fig. 2 displays the electron density (n_e) as a function of fractional Ar pressure in H_2/Ar plasma under different working pressures. The electron density is measured by a Langmuir probe. From the I–V characteristic, the electron energy distribution is found applying Druyvesteyn formula. Integrating the electron energy distribution function gives the electron density [3], [8]. Increasing Ar content implies increasing electron density n_e for all working pressures. In general, n_e is an indication of the amount of all positive ions (Ar^+, H^+, H_2^+ and H_3^+) in the plasma neglecting negative ions. The increase in n_e can be attributed to the increase in the amounts of the dominant ions H_2^+ and H_3^+. This finding reveals that adding Ar can enhance the generation of hydrogen ions. Notably, the ratio of H_3^+/H_2^+ is about 1.48 in H_2/Ar plasma. Owing to the increases of H_2^+ and H_3^+ in the plasma, the amounts of H_2^+ and H_3^+ reaching the wafer surface increase as well. H_2^+ and H_3^+ then dissociate to H and H^+ to perform hydrogenation when they impact the wafer surface [9]–[13].

In a conventional H_2/Ar parallel-plate discharge, the ion density is low, i.e., around 1.0×10^{15} m^{-3}. Passivation of tail states which affect μ_{FE} occurs with an onset time of several hours until a large fraction of midgap states have been passivated [1]. However, in this work, μ_{FE} is improved by approximately 27% after H_2/Ar hydrogenation for 20 min in an inductive discharge. Because ICP is a high-density plasma with an electron density of 6.5×10^{17} m^{-3}, both midgap and tail states can be simultaneously passivated. Consequently, the passivation rate is enhanced. However, the high-density plasma can easily damage devices during hydrogenation, but according to our results, the gate leakage current remains nearly unchanged after ICP hydrogenation. Furthermore, our results demonstrate that the high-density ICP plasma doesn't damage the gate oxide. The ion bombarding energy from the H_2/Ar plasma is roughly 18 eV [14] which is significantly lower than expected in a conventional parallel plate discharge.

Herein, the maximum substrate temperature was maintained at around 295 °C during hydrogenation. In general, temperature control is critical to the hydrogenation process. To further enhance passivation efficiency, TFT's were annealed at 350 °C for 30 min after the H_2/Ar hydrogenation. Experimental results indicate that N_t of TFT's reduces from 1.16×10^{13} cm^{-2} to 1.02×10^{13} cm^{-2} after annealing. Moreover, reliability is an important issue for TFT's after hydrogenation. Fig. 3 displays the N_t as a function of stress time for H_2/Ar hydrogenated TFT's before and after 350 °C annealing. Stressing is examined with $V_{\rm ds} = V_{gs} = 12$ V. For TFT's without 350 °C annealing, N_t increases rapidly with stress time. This increase implies that the Si–H bonds in the channel can be easily broken by the transport carriers resulting in the regeneration of trap states [15]. For post-annealed TFT's, N_t increases more slowly with stress time because the Si–H bonds are strengthened by annealing and difficult to be broken by the transport carriers. This finding confirms that the reliability of TFT's is enhanced after post-hydrogenation annealing.

In summary, in this work, the trap states in poly-Si TFT's are effectivly reduced by combining inductive discharge and the Penning effect to perform hydrogenation. During hydro-

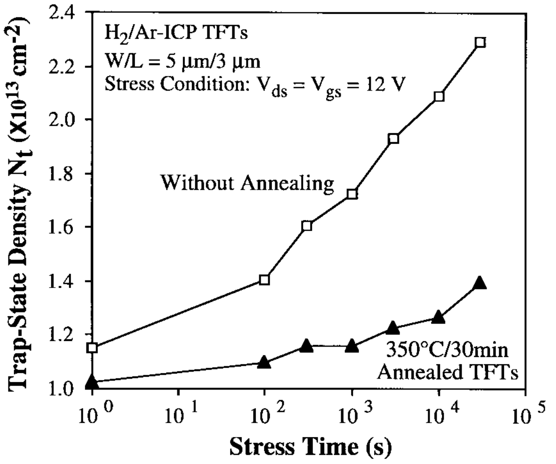


Fig. 3. Trap-state density as a function of stress time for H_2/Ar-ICP hydrogenated poly-Si TFT's before and after annealing at 350 °C for 30 min. The stress bias is $V_{ds} = V_{gs} = 12$ V.

genation, adding Ar gas into the H_2 plasma promotes the generation of hydrogen ions. Therefore, midgap states and tail states are simultaneously passivated. In addition, the post-hydrogenation anneal is utilized to further enhance passivation efficiency, as well as improve the reliability of TFT's. We conclude that planar inductive discharge of H_2/Ar mixture is highly promising for hydrogenation technology of poly-Si TFT's.

REFERENCES

[1] I. W. Wu, T. Y. Huang, W. B. Jackson, A. G. Lewis, and A. Chiang, "Passivation kinetics of two types of defects in polysilicon TFT by plasma hydrogenation," *IEEE Electron Device Lett.*, vol. 12, p. 181, Apr. 1991.
[2] R. A. Ditizio, S. J. Fonash, and B. C. Hseih, "Examination of the optimization of thin film transistor passivation with hydrogen electron cyclotron resonance plasmas," *J. Vac. Sci. Technol. A*, vol. 10, no. 1, p. 59, 1992.
[3] J. T. Gudmundsson, "Experimental studies of H_2/Ar plasma in a planar inductive discharge," *Plasma Sources Sci. Technol.*, vol. 7, p. 330, 1998.
[4] J. Hopwood, "Review of inductively coupled plasmas for plasma preocessing," *Plasma Sources Sci. Technol.*, vol. 1, no. 2, p. 109, 1992.
[5] C. F. Yeh, S. S. Lin, and C. L. Fan, "Thinner liquid phase deposited oxide for polysilicon thin-film transistors," *IEEE Electron Device Lett.*, vol. 16, p. 473, Nov. 1995.
[6] Y. Okamoto and H. Tamagawa, "Production of large area high current ion beams," *Rev. Sci. Instrum.*, vol. 43, no. 8, p. 1193, 1972.
[7] W. S. Barnes, D. W. Martin, and E. W. McDaniel, "Mass spectrographic identification of the ion observed in hydrogen mobility experiments," *Phys. Rev. Lett.*, vol. 6, no. 3, p. 110, 1961.
[8] M. A. Lieberman and A. Z. Lichtenberg, *Principles of Plasma Discharges and Materials Processing.* New York: Wiley, 1997, p. 177.
[9] E. S. Cielaszky, K. H. R. Kirmse, R. A. Stewart, and A. E. Wendt, "Mechanisms for polycrystalline silicon defect passivation by hydrogenation in an electron cyclotron resonance plasma," *Appl. Phys. Lett.*, vol. 67, no. 21, p. 3099, 1995.
[10] H. Hirayama, "Dissociative scattering of H_3^+ molecular ions from the Si(100) surface," *Phys. Rev. B*, vol. 48, no. 11, p. 8095, 1993.
[11] O. Yenen, L. M. Wiese, D. Calabrese, and D. H. Jaecks, "Near-zero energy proton production mechanisms from the three-body dissociation of H_3^+," *Phys. Rev. A*, vol. 42, no. 1, p. 324, 1990.
[12] C. Bordas, P. C. Cosby, and H. Helm, "Measurement of the lifetime of metastable triatomic hydrogen," *J. Chem. Phys.*, vol. 93, no. 9, p. 6303, 1990.
[13] H. Yamada, "Low-temperature surface cleaning method using low-energy reactive ionized species," *J. Appl. Phys.*, vol. 65, no. 2, p. 775, 1989.
[14] J. T. Gudmundsson, "Ion energy distribution in H_2/Ar plasma in a planar inductive discharge," submitted for publication.
[15] I. W. Wu, W. B. Jackson, T. Y. Huang, A. G. Lewis, and A. Chiang, "Mechanism of device degradation in n- and p-channel polysilicon TFT's by electrical stressing," *IEEE Electron Device Lett.*, vol. 11, p. 167, Apr. 1990.