Manufacturing Process of Flat Display∗

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A large size display for entertainment, internet, PC and other information instruments is key tool for coming IT revolutionary era, so that the large size display must be characterized by very low electric power consumption and human friendly performance without tiring user’s eyes. Thus, liquid crystal (LC) and electroluminescence (EL) displays are candidates for this target. High quality poly-silicon TFT is essentially required even for LCD displays instead current amorphous Si TFT, because very large current drivability is necessary for TFT due to the increase of LCD cell capacitor with an increase of display size up to 50 inches and beyond. The key issue for this target is a creation of very low temperature poly-Si TFT manufacturing technology without excimer laser annealing and very low cost manufacturing which is characterized by very simplified display structures and very simplified manufacturing steps based on very drastic progress of various relating materials and components such as backlights, polarizer, color filter, and etc.

Key Words: Radical Reaction, Poly-Silicon, TFT, Flat Display

1. Introduction

A large-size and multi-purpose display lager than 30 inches at least which can be connected to any information media such as entertainment programs, internet, PC, PDA and so on is strongly required for coming IT revolutionary era. This is because the information provided from such media is strongly depending on the eyesight of human beings. In order to select the exact information at a moment from numerous one, the large-size panel will be required to display the information from such multimedia. Since almost of all users will stare at such display all the day for entertainment or for job, the power consumption must be reduced as low as possible for the environment-friendly system. Of course, such display panel is required to have human-friendly performance; for example, all day long watch gives no tiredness to the user’s eyes.

The liquid crystal display (LCD) and the electroluminescence display (ELD) are the candidate for such large-size panel and many reports are eagerly presented by the many researchers(1)-(3). However the production cost is too high to spread such large-sized display to all over the world, therefore the new manufacturing methodology is required for very low cost manufacturing as well as an introduction of simplified panel structures.

An increase of display’s size will accompany an inevitable increase of cell size, i.e., an increase of cell capacitance, so that the poly-Si TFT having large current drivability is essentially introduced even to LCD displays. Radical reaction based manufacturing technologies must be introduced to poly-Si TFT manufacturing, where very high quality processes such as direct surface oxidation and nitridation, poly-Si, SiO₂ and Si₃N₄ CVD film formations, and reactive ion etching (RIE) free from surface damages and pattern and material dependence of process uniformity have been confirmed available at very low temperatures around 200°C to 400°C. Particularly, radical reaction based direct surface oxidation can provide very high quality SiO₂ films at very low temperature on entire crystal orientation silicon surface, while current molecule reaction based thermal oxidation can produce high quality SiO₂ films only on (100) Si surface but not for any other crystal orientation Si surface.

Poly-Si films essentially include various crystal orientation grains. Thus, the newly developed radical reaction based manufacturing becomes available by the development of microwave excited high density plasma with very low electron temperatures less than 1.0 eV(6).
2. Low Electron Temperature and High-Density Plasma Equipment

In the current semiconductor devices and processes, very large threshold voltage fluctuation of MOSFETs is originated from some plasma processes in BEOL (Back End of Line)\(^7\),\(^8\). Current plasma equipment cannot be used for FEOL (Front End of Line) because they cause too huge amount of damages to the Si substrates surfaces.

The requirements for plasma equipment used for FEOL are shown as follows;
1. Surface damage free
2. Metal contamination free
3. Charge-up damage free
4. Process uniformity independence to surface patterns and materials
5. Free from threshold voltage fluctuation of MOS transistor

The requirements for equipment satisfying the above-mentioned items are shown as follows,
1. The electron temperature in process region is at least less than 1 eV in order to decrease the bombarding ion energy onto the substrate surface given by Eq. (2) less than 7 eV, where 7 eV is the critical energy of Ar ion to generate surface damages on SiO\(_2\) films. The critical energy of Ar ion to generate surface damages is 12 eV for Si\(_3\)N\(_4\) films and 25 eV for single crystal Si, respectively.
2. The process region is separated from the plasma excitation region.

Such equipment has been developed by the microwave plasma excitation using the radial line slot antenna (RLSA) emitting circularly polarized electromagnetic waves. (Since electron temperature is too high, don't use the plasma excited by the electron cyclotron resonance) and by using Kr and Xe gas whose electron collision cross-sections are about 2 and 4 times larger than that of Ar gas, respectively, resulting in realizing very low electron temperature plasma\(^9\). The recovery recycling system of Kr and Xe gases which recycling rates must be greater than 99.9% and 99.99%, respectively, has been developed in parallel because the prices of Kr and Xe gases are 1000 and 10 000 times higher than that of Ar gas. Key technology to realize the recovery and recycling system having such high recycling rate is to develop new gas pumps characterized by very small purge gas flow rate less than 1 L/min, current back pumps require huge amount of dilution gas flow rate greater than 15 L/min and/or 20 L/min in order to obtain gas pumping capability even for very small molecule weight gases such as hydrogen (H\(_2\)) and helium (He) similar those of N\(_2\), Ar, etc. Figure 1 shows the schematic diagram of the developed low-electron temperature and high-density plasma equipment\(^6\),\(^8\).

Figure 2 shows the electron temperature (a) and the electron density (b) as a function of the distance from the dielectric plate in the plasma with 0.5 Torr of Ar atmosphere and an input power density of 1.27 W/cm\(^2\) for 2.45 and 8.3 GHz of the microwave frequency. The plasma excitation is taken place in less than 20 mm distance from the shower plate. 94–95% of microwave power is used for plasma excitation, 5–6% of the remaining microwave electric power is fully reflected by exited high density plasma, and it does not penetrate into an inside. It is because the plasma frequency expressed with a formula (1) is enough higher than 2.45 GHz and 8.3 GHz.

\[
\omega_p = \left( \frac{n_e e^2}{m_e \varepsilon_0} \right)^{\frac{1}{2}}
\]  

(1)

Where \(n\) is the electron density, \(m_e\) is the electron mass, and \(\varepsilon_0\) is the dielectric constant of vacuum.

An electron temperature keeps a fixed value by nearly 1.0 eV for depth regions separated from shower plate greater than 20 mm. It means that the region is a perfect diffusion plasma region. Even if excitation frequency is raised from 2.45 GHz to 8.3 GHz, the electron temperature of diffusion region plasma decreases only by about 0.1 eV. However, when the excitation gas is changed to Kr and Xe gases which have the electron collision cross-section area of about a twice and 4 times larger than that of Ar gas, the ultra low electron temperature plasma which decreases down to the electron temperature of 0.7 eV and 0.5 eV can be realized by the 2.45 GHz micro-wave excitation. The silicon wafer treated in this equipment is placed in the depth region of 40 to 60 mm from the shower plate. Then, the wafer is perfectly separated from a plasma excitation region and treated in a diffusion plasma region.
The secondary electrons generated by the ion bombardment to the silicon surface do not contribute to plasma excitation at all, and then a uniform process is guaranteed also to the entire substrate surface that has any pattern and any material. Since the electron current and ion current which flow into the substrate surface placed in the diffusion plasma region are mutually cancelled with each other in an instant, even if they erase plasma at any moment, an electric charge is not remained on the substrate surface and charge-up damage is not generated. Since electron temperature becomes low enough with 1 eV or less, the ion energy that irradiates the substrate surface and the inner surface of the chamber becomes sufficiently small, and then substrate surface damage and substrate surface metal contamination are not generated at all. An ion energy that irradiates the substrate surface in a floating state is expressed by following equation.

\[ \frac{e_{\text{bob}}}{2} = \frac{K T_e}{3} \ln \frac{m_i}{\alpha_0 3 m_e} \]

Where, \(m_i\) is the mass of ion. This equation means

\[ \epsilon_{\text{bob}} = \frac{K T_e}{2} \ln \frac{m_i}{\alpha_0 3 m_e} \]

(a) Electron temperature in depth direction

(b) Electron density in depth direction

Fig. 2 Electron temperature and electron density as a function of the distance from the dielectric plate in the plasma conditions with atmosphere of Ar

that the ion energy is proportional to the electron temperature \(T_e\). Figure 3 shows threshold voltage \(V_{TH}\) fluctuation of MOSFETs after various plasma irradiations for 10 min. The \(V_{TH}\) fluctuation of the prepared MOSFETs before the irradiations is less than 0.02 V. After Ar plasma excited by conventional parallel plate (13.56 MHz, electron temperature: 3–5 eV) irradiation, the fluctuation of \(V_{TH}\) increases up to 0.7 V. The three remaining data are shown for the microwave-excited plasma. When He gas whose collision cross section is less than 1/5 of that of Ar gas is used as plasma excitation \(V_{TH}\) the electron temperature becomes 1.5 eV, and then the fluctuation of \(V_{TH}\) increases to 0.3 V. When Ar gas is used as excitation, the electron temperature becomes 1.0 eV, and then the fluctuation of \(V_{TH}\) increases to 0.02 V. In the case of Kr and Xe gas, the electron temperatures become 0.7 and 0.5 eV, respectively and do not increase the \(V_{TH}\) fluctuation.

Figure 4 shows the \(1/f\) noise characteristics of MOSFETs with the gate insulator of conventional dry oxide, wet oxide, and the oxynitride formed by Kr/O2/NH3 plasma. The \(1/f\) noise power in MOSFET with oxynitride formed by Kr/O2/NH3 plasma at 400°C is 1–2 orders of magnitude less than those with conventional
thermal oxides. This means that the $1/f$ noise can be reduced only changing the gate insulator from the conventional oxides to the insulators formed by this microwave-excited plasma. This microwave-excited plasma equipment with very low electron temperature ($<1$ eV) and high density ($>10^{13}$ cm$^{-3}$) is essentially required for a radical reaction based processing for future flat panel display manufacturing to generate various radicals very effectively.

In Fig. 5, the oxide film thickness is plotted as a function of oxidation time for thermal oxidation at 900°C and oxygen radical oxidation at 400°C on various substrate surfaces such as single crystal silicon surfaces of (100), (110) and (111), and highly doped n$^+$ poly-silicon$^{13,14}$. It is clearly seen from Fig. 5 that the oxidation speed is maintained almost same for all substrate surfaces in the radical reaction based oxidation while the oxidation speed is completely different for different substrate surfaces in the current molecule reaction based thermal oxidation. Figure 6 shows the current density-electric field intensity characteristics of the oxide films formed on highly doped n$^+$ poly-silicon by the radical reaction based oxidation at 400°C and the current molecule reaction based thermal oxidation at 900°C. It is seen from Fig. 6 that the oxide film quality obtained by the radical reaction based oxidation is completely superior to that obtained by the current thermal oxidation, i.e., the leakage current density is improved by an introduction of the radical reaction based oxidation by 6 orders of magnitude at around 6 MV/cm. The radical oxidation film quality on the highly doped n$^+$ poly-silicon is completely similar to that of the current thermal oxide films obtained on (100) single crystal silicon surface at 1000°C$^{14}$.

3. High Density Microwave Excited Plasma Equipment with Dual Shower Plate for Plasma CVD and RIE Processes

Low electron temperature and high density plasma equipment can be used for the very high quality plasma enhanced CVD (PECVD) and the very high quality reactive ion etching (RIE) processes by adding a lower shower plate to a diffusion plasma region (shown in Fig. 7). By introducing the RF bias to the substrate stage, this equipment can be used for the RIE process$^{8}$. Without RF bias, this can be used for the PECVD process$^{8}$. Figure 8 shows the breakdown characteristics for the SiO$_2$ films having a thickness of 20 nm formed by PECVD at 400°C and the thermal oxidation on single crystal silicon substrates. Both the breakdown field ($E_{BD}$) and the charge-to-breakdown ($Q_{BD}$) of the PECVD SiO$_2$ films are the same as those of the thermal SiO$_2$ films.

Figure 9 shows the current density ($J$)-electric field intensity ($E$) characteristics for the SiO$_2$ films formed by PECVD and the thermal oxidation on highly doped n$^+$ polycrystalline silicon. The current density of the PECVD oxides is much less than that of the thermal oxides by
Fig. 8 Breakdown characteristics for the SiO₂ films formed by PECVD and the thermal oxidation on single crystal silicon substrates.

Fig. 9 J–E characteristics for the SiO₂ films formed by PECVD and the thermal oxidation on polycrystalline silicon. Si/SiO₂ interface roughnesses of both a factor of 6 orders of magnitude. The Si/SiO₂ interface roughnesses of both samples are also shown in Fig. 9. A grain growth is occurred in the high temperature thermal oxidation process, and then the larger roughness of Si/SiO₂ interface is generated. In the case of PECVD process, migration of Si atoms cannot be occurred because of very low process temperature of 400°C(15).

Figure 10 shows the capacitance (C)–voltage (V) characteristics and J–E characteristic for the silicon nitride films formed by PECVD at 400°C. The silicon nitride films formed by PECVD radical reaction based nitridation have small hysteresis of C–V curve and shows the very good J–E characteristics. It is seen from Fig. 10 that the breakdown field intensity of nitride-film having thicknesses of 6 to 10 nm is completely greater than 15 MV/cm(16).

Figure 11 shows relation between O₂ gas flow rate and Vdc with respect to the state of the hole concentration of boron-doped p⁺-Si surface after the radical reaction based reactive ion etching of SiO₂ film using Ar/C₅F₈/O₂ gas(17,18). In the figure, O represents that the hole concentration was not degraded, while X represents that the hole was deactivated due to ion bombardment. In addition, the boundary between etching mode and deposition mode in case of the SiO₂ substrate is indicated by the dotted line. From the results, a condition of damage-free etching which can suppress deactivation of hole concentration on p⁺-Si surface is found in the region of O₂ flow rate of 10 sccm and Vdc = −200 V. Contact hole etching was carried out by combining with the high-speed etching mode having Vdc lager than −500 V and damage-free etching mode having Vdc of around −200 V. Figure 12 shows cross sectional SEM image of 350 nm SiO₂ contact hole. First, 90% of SiO₂ was etched with etching rate of about 450 nm/min under the condition that Vdc = −440 V (Pₑ₀ = 0.4 kW) as shown in Fig. 12 (a). Next, remaining 10% SiO₂ was etched with damage-free etching mode under the condition of Vdc = −210 V (Pₑ₀ = 0.12 kW) as indicated in Fig. 12 (c). Cross sectional SEM image of contact hole etching after the Ar/O₂ plasma ashing is shown in Fig. 12 (b). Contact hole was successfully etched using two-step etching modes without accompany-
ing degradation of hole concentration of p⁺ region.

These indicate that the PECVD and the etching processes using the high-density microwave excited plasma equipment with dual shower plates are very effective for very high quality film formations at very low temperatures formation and pattern formation of various devices without accompanying damages.

4. Conclusion

We have demonstrated very excellent performances of radical reaction based processings using high density and very low electron temperature plasma (less than 1.0 eV) obtained by microwave excitations, where very high quality direct oxidation films (SiO₂) have been confirmed to be obtained even on poly-silicon films at very low temperatures around 200°C to 400°C by using single shower plate structure equipment, and very high quality various CVD films have been demonstrated to be formed on various substrate surfaces at very low temperatures at around 200°C to 400°C by dual shower plate structure equipment. Generally speaking, these film qualities are superior to those of current various films obtained on single crystal silicon substrates at high temperatures around 1000°C. Moreover, damage free reactive ion etching becomes available.

Thus, newly developed radical reaction based processings will realize very high quality poly-silicon TFT on glass substrates at low temperatures without excimer laser annealing, so that very high quality large size FPDs of LCD and OLED will be developed within very near future.

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References

S., Aharoni, H. and Ohmi, T., Low Temperature Growth (400°C) of High-Integrity Thin Silicon-Oxynitride Films by Microwave-Excited High-Density Kr/O_2/NH_3 Plasma, IEEE the 22nd Convention of Electrical and Electronics Engineers in Israel, (2002), pp.166–169.


