Sputtering Technology of Si Films for Low-Temperature Poly-Si TFTs

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Abstract

In this paper we discuss the development of sputter-Si technology for application in the area of poly-Si TFT Liquid Crystal Displays. We present the motivation behind this development and the state-of-the-art in materials and devices, based on PVD-Si precursor material. The Si-sputtering process is analyzed and data are presented on the quality of as-sputtered and post-annealed Si-films. The current drawbacks of Si sputtering are discussed, especially with respect to particles, film contamination and equipment availability. Based on the available data, strategies are presented to overcome these problems. PVD-Si technology has come a long way and has become a viable candidate as a Si-deposition method for next generation of poly-Si based applications. This technique is expected to play an even more important role, as the p-Si TFT-LCD industry moves to ultra-low temperature processing and, in parallel, the need increases for process cost reductions.

Introduction

Physical Vapor Deposition, or sputtering, is a deposition technique that is widely used in the thin film industry. A good treatise on sputtering can be found elsewhere1). PVD relies on the bombardment of a target, made of the material to be deposited, primarily by energetic ions, which are generated by the ionization of a working gas under an applied voltage. The target, upon bombardment, ejects atoms of the target material, which then float and condense on a substrate that is placed opposite to the target.

Unlike other deposition methods, sputtering does not involve chemical interaction among the species. Even the so-called "reactive" sputtering follows the same deposition principle described above. The bombardment of the target with energetic ions ejects equally energetic atoms, which eventually condense and deposit their energy on the film formed on the substrate. This source of energy can compensate traditional energy sources, such as heating, that are required to promote film growth and improve film characteristics. Hence, sputtering can be used to deposit good quality films at moderate (<500°C), to very low temperatures (<300°C), even down to room temperature. This enables compatibility with a wide variety of substrates and makes sputtering a promising technology for such applications.

Intrinsically, Si sputter deposition offers 4 advantages: (a) elimination of toxic/hazardous process gases, (b) reduction in process temperature, (c) ability to control amount of H_2 incorporated in the deposited film, (d) ability to pre-dope the Si film. These advantages translate to potential benefits in equipment and maintenance cost, improved factory/worker safety and, quite importantly, process reduction by elimination/grouping of several process steps in one. Even though a-Si TFT-LCD technology is not particularly drawn to Si sputtering, p-Si TFT-LCD technology seems to have more to gain by adopting this technology. We believe that this due to a combination of reasons, such as:

1. Polysilicon technology requires precursor Si material with very low H_2-content, unlike a-Si technology where the opposite is sought. This makes sputtering ideal technology, as the H_2 content is extremely low (<1at%) and, moreover, controllable[2].
2. Sputtering is one of the few techniques that can deposit good quality Si-films at temperatures as low as room temperature. This is important for future applications requiring films to be deposited on heat-sensitive substrates[3].
3. Sputtering is an area-scaleable technique and can be used either with single-substrate processing or roll-to-roll processing concept.
4. Sputtering from doped targets allows for deposition of lightly doped Si films. In this manner, the Vth-adjustment doping step can be merged with the deposition step to reduce processing steps and total cost.
5. Poly-Si flow typically requires more process steps than a-Si flow. Hence, process reduction is more important, for cost control, to poly-Si process flow.
6. Poly-Si process has not reached the level of maturity of a-Si process. The process flow is still open to new technologies such as sputtering.

These gains should be compared and contrasted to the potential issues/drawbacks associated with Si sputtering. These are active areas of research and solutions to these issues are key to the implementation of sputtering to poly-Si TFT-LCD technology. We recognize four such areas:
1. Particle reduction and control during Si sputtering.
2. Simultaneous optimization of film quality, process throughput and device performance.
3. Development of sputtering technology is necessary not only for Si precursor but also for relevant dielectric films (i.e. SiO_2, SiN_x, etc.).
4. Development of Si-precursor/dielectric film sputtering equipment for mass production.

In this paper we describe the state-of-the-art developments in sputtered Si-precursor technology for application in p-Si AM-LCDs. Film characteristics are shown and the corresponding electrical performance of fabricated p-Si TFTs is presented. Equipment issues are discussed from the points of view of sputtering practices and particle control. Guiding principles for equipment design are then presented. Finally, we conclude on the current status and comment on the remaining challenges and future opportunities.

1. PVD-Si FILM CHARACTERISTICS

1.1 As-sputtered Si films

Fig. 1 shows deposition rate data for DC sputtered Si films. The deposition rate scales linearly with the power with a coefficient of 2.8Å/kW-s. It should be noted that very high DC-power is not necessarily desirable, as high deposition rates (in the order of 12-18Å/sec) can be readily obtained in the range of 4-6kW. These deposition rates are sufficient for high throughput and are comparable with rates currently afforded by the PECVD method (~10Å/sec). However, there are also other considerations for the selection of power level, including particle generation (discussed later) and overall film quality.

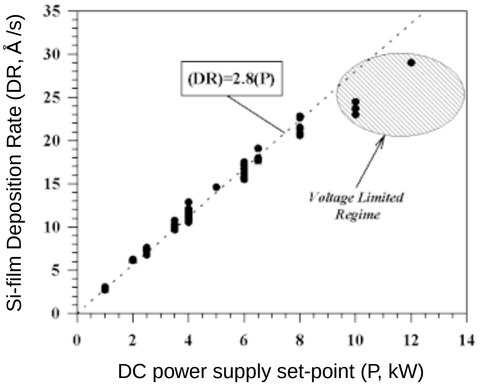

Fig.1 PVD-Si Dep. Rate-vs.-Power.

The process pressure also affects the sputtered Si-film rate. The deposition rate decreases as the sputter pressure increases. However, even most importantly, sputter pressure is the main parameter controlling the degree of incorporation of sputtering gas in the deposited film4)5). **Fig. 2** shows relevant data for the case of Si sputtering in Ar gas2)5)6). As expected, Ar incorporation decreases with increasing pressure. This is attributed to the increased gas-phase collision between energetic Ar ions and neutral Si atoms in the plasma region between target and substrate. Furthermore, as **Fig. 2** suggests, gas incorporation increases as the working gas ions are accelerated at higher voltage.

The main mechanism of Ar incorporation in sputtered films is via collision of sufficient kinetic energy ions or neutrals with the growing film4). Such energetic ions/neutrals are backscattered upon collision of Ar ions with the Si-target. We have conducted simulations of the backscattered atom energy distribution using TRIMTM software. In this case, the incoming sputtering-ion energy was specified and the number and energy of backscattered atoms was recorded via the simulation software. With this information, the energy distribution and the average energy of the backscattered atoms was calculated as a function of the mass and the incoming energy of the ions directed towards the Si target. Once the energy distribution of the backscattered ions/neutrals is known one can use it to estimate the amount of energy that these energetic species deposit on the surface of the sputtered film. This energy can then be compared to the energy required to affect microstructural changes in the deposited Si-film (i.e. to 3.5-4.7eV, which is the estimated Si-Si bond strength). As shown in **Fig. 3**, Ar reflected atoms could affect microstructural changes in as-sputtered Si films, as they possess sufficient momentum to break Si-Si bonds, upon collision with the Si atoms in the deposited film. This points to the important conclusion that the energetic Ar atoms are not only responsible for undesirable Ar incorporation in the film but also for desirable modifications in the microstructure of the as-sputtered Si films. Substituting Ar with a lighter inert gas (i.e. He) to minimize the gas incorporation problem, can adversely affect the quality of the sputtered Si film. This is implied by the results in **Fig. 4**, where it is clearly shown that He atoms do not possess enough

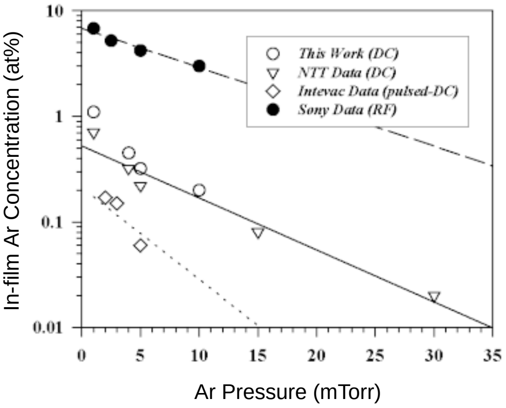

Fig.2 In-film Ar content as a function of sputtering method and process pressure.

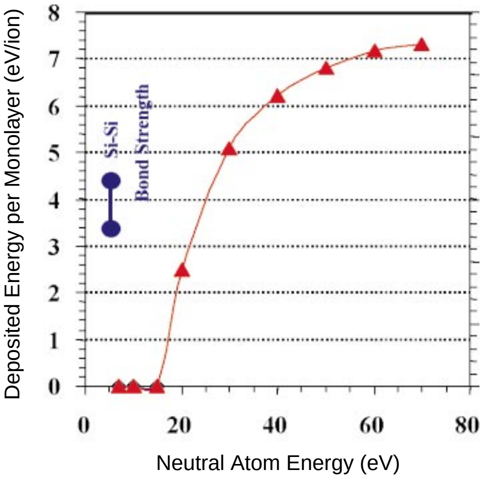

Fig.3 Relationship between reflected Ar atom energy and energy deposited on sputtered film.

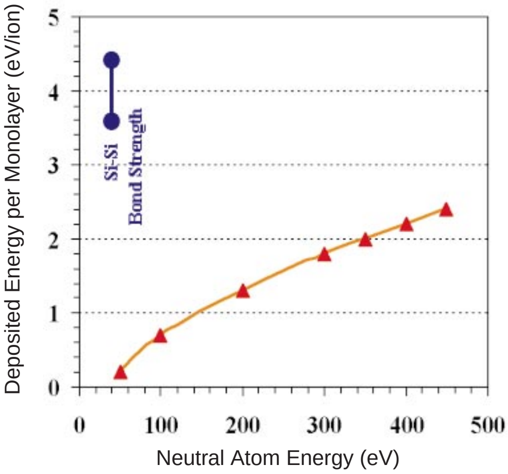

Fig. 4 Relationship between reflected He atom energy and energy deposited on sputtered film.

energy to densify or otherwise modify the microstructure of the sputtered Si-film.

With this information, we can conclude that as the Ar pressure increases (to reduce the Ar content) another way needs to be provided to preserve the "quality" of the film. This could be accomplished by increasing the deposition power to appropriate levels, guided by the principle described in **Fig. 3**. Such improvement is indicated in **Fig. 5**, which plots the refractive index of as-sputtered Si films as a function of the pressure and DC-power. The refractive index is a measure of the density of the film, hence, in extension, the quality of the film⁵⁾. As the Ar-pressure increases, the refractive index decreases and higher power is required to restore it to its original value. Notice that at high pressures (>5mTorr), not even 10kW is sufficient to restore the n-index.

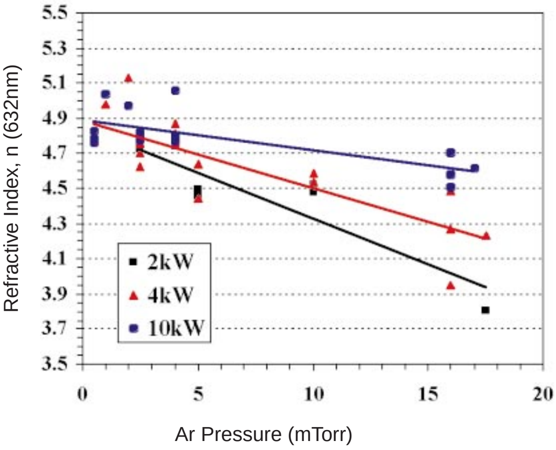

Fig. 5 Refractive index of sputtered Si-films as a function of Ar-pressure and DC-power.

The quality of the film is also governed by the substrate temperature. Temperature does not impact the deposition rate. However, it has strong impact on the microstructure according to the postulates of the structure-zone-model (S-Z model)⁷⁾. Hence, higher deposition temperature is generally preferable (i.e. up to 400°C).

1.2 Post-Annealed PVD-Si films

Sputtered-Si films are quite difficult to crystallize by means of solid-phase-crystallization. Typically, high temperature and/or long annealing time are necessary for complete phase transformation. This is primarily attributed to sputtering gas incorporation in the film, as well as to the high degree of structural disorder in the a-Si network due to deposition at low temperatures and with high rates⁸⁾. As a result, laser-annealing technique is more appropriate for the crystallization of PVD-Si films. In this manner, it is possible to take advantage of the higher absorption coefficient of PVD-Si films to reduce the laser energy density that is required to sufficiently melt the thin films. In the past, both continuous lasers (i.e. CW-Ar) and pulsed lasers (i.e. excimers, such as XeCl and KrF) have been successfully used with PVD-Si precursor⁹⁾.

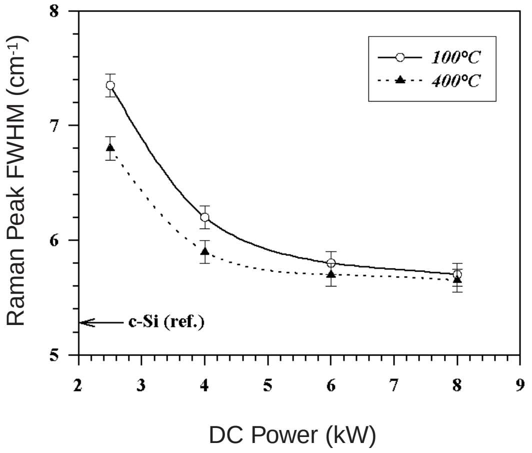

Fig. 6 Raman FWHM of post-ELA sputtered-Si films versus DC-power and substrate temperature.

Fig. 6 shows the crystalline characteristics of post-ELA sputtered-Si films as measured by Raman spectroscopy. The FWHM of the Raman peak is reported and shown to decrease as the DC power and/or the deposition temperature increase. Narrower peak (smaller FWHM) corresponds to better crystalline quality (including grain size and crystal defect density). It appears that the quality of the polycrystalline structure, after laser annealing, correlates with the initial microstructure of the as-sputtered Si film. PVD-Si films deposited at low temperature and/or low power tend to develop higher density of voids. This most likely affects the characteristics of the polysilicon film despite of the melt/recrystallization process that the film undergoes when subjected to laser-annealing process.

1.3 Particle Generation and Control

Particle generation is one important issue that plagues sputtered-Si deposition process from implementation in mass production. Si material is brittle and can easily produce particles during deposition. Mild or hard arcing in the chamber is another source of particle formation. The probability of arcing in DC-mode significantly increases, as the target material becomes more resistive (as in the case of lightly doped Si). Particles can also be generated due to film peeling off from the various surfaces, within the chamber, exposed to plasma. In the case of sputtering over large areas, tiled Si targets are typically used, which introduces another source of particles. These are particles formed at the edges of Si-tiles due to stresses developing over the life of the target (leading to edge cracking) or residual mechanical damage from the tile cutting and edge-finishing process.

We have conducted a number of particle tests simulating deposition of approximately one week's mass production processing. This corresponds to ~4,000 Si-films, or (at 500Å each) to ~200 μm of total film deposition. In this study we used a horizontal type cluster tool. We investigated the particle counts at given intervals throughout the test. In addition, we investigated particle counts as a function of applied power to the Si-target. These results are summarized in **Fig. 7** and **8**.

The main conclusion from this study is that PVD-Si process tends to generate small particles (i.e. less than 1μm), which, although remain steady over long deposition periods, are above the desirable level. Moreover, these particles multiply as the DC-power increases. At DC-power levels necessary to maintain the throughput, the particle levels are currently unacceptable. Switching to p-Si target material is not helpful as far as small particles and, moreover, tends to enhance formation of large particles. Hence, the principle solution to the intrinsic Si-particle formation is the utilization of vertical deposition chamber architecture. Development of such equipment is currently in progress for Si sputtering2). Additionally, equipment makers who are currently selling equipment in the optical or disc coatings industry may be willing to tackle this problem using their experience with relevant thin film coatings (SiN_x, SiO_2, etc.).

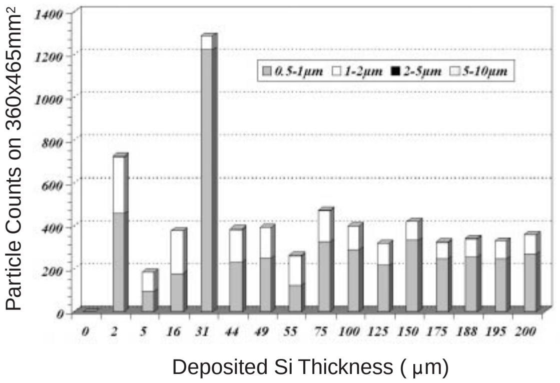

Fig. 7 Particle data from a c-Si target obtained during a 200μm sputtering-marathon.

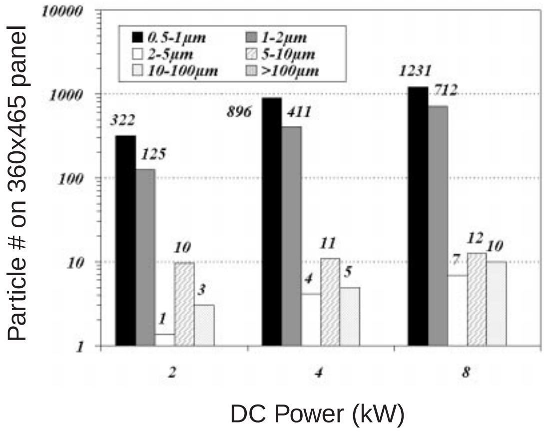

Fig. 8 Particle counts from a c-Si target as a function of applied DC-power.

The total results obtained from material characteristics, particle performance, film contamination, anode design, target considerations and general system maintenance lead to a number of basic system requirements for PVD-Si deposition:

1. The Si-target needs to be small, consisting of as few tiles as possible. This approach lowers the material and fabrication costs and improves ease of replacement/maintenance. Continuous sputtering of the target is

preferred to avoid surface oxidation and prevent microarcing.

2. Uniform gas flow is required to alleviate plasma and film non-uniformity, especially for reactive sputtering applications.

3. Vertical chamber configuration is necessary for Si-particle reduction and control.

4. Improved anode designs are needed to alleviate the problem of the disappearing anode, common in sputter-deposition of resistive materials. Alternative designs (such as dual cathode, or similar concepts) may be necessary to completely eliminate this problem. Elimination of the metal anode can also resolve the metal contamination issue.

5. Tool design should be compatible with high frequency pulsed DC power supply. Pulsed-DC mode is commonly used in deposition of insulating films, as an alternative to RF sputtering.

2. PVD-Si TFT CHARACTERISTICS

In this section we present the characteristics of poly-Si TFTs made with laser-crystallized PVD-Si precursor. Very good TFT results have been obtained using various TFT fabrication flows and a wide process temperature range. Good data consistency was observed, after an initial optimization period. The average mobility over a number of TFT lots is around 150cm^2/Vs and the corresponding threshold voltage is in the range of 2.5V. Our data are in good agreement with other studies [2,6,10,11]. The current level of interest in the industry and the general data agreement, we believe are good indicators of the bright future of PVD-Si technology.

We also fabricated pMOS p-Si TFTs and the characteristics of pMOS and nMOS TFTs are compared in **Fig. 9**. The mobility of pMOS TFTs is in the order of 60cm^2/Vs. The threshold voltage is centered on -2 to -3V. This value is in excellent agreement with that of nMOS

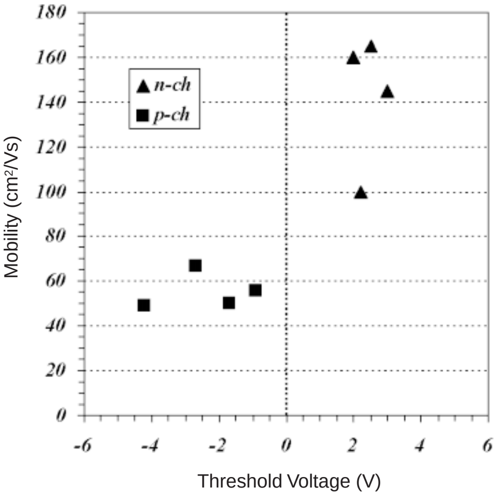

Fig. 9 Characteristics of nMOS and pMOS p-Si TFTs fabricated with PVD-Si precursor (45-nm thick films, deposited at 400°C).

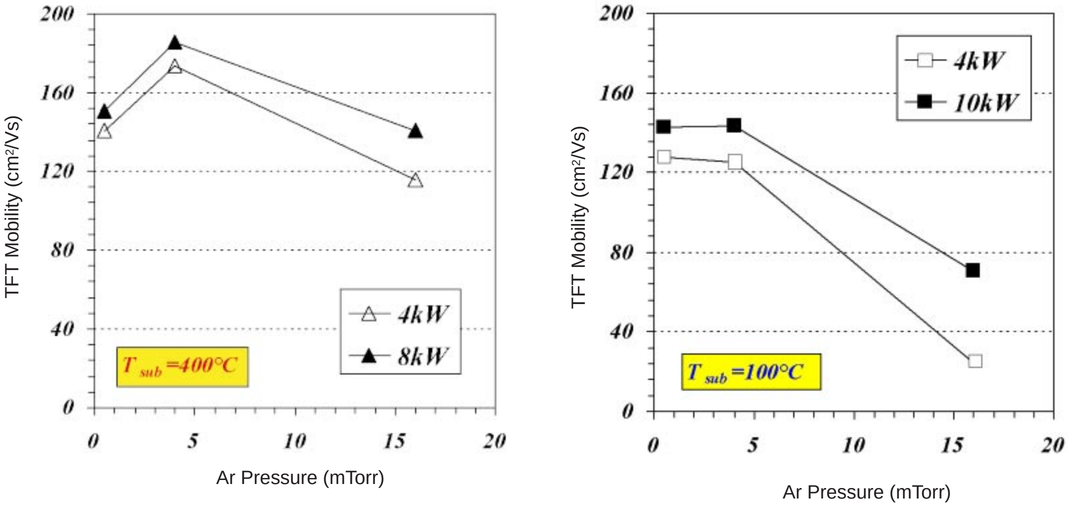

Fig. 10 Characteristics of p-Si TFTs as a function of sputter pressure and DC-power. (top) T_{dep}=400°C; (bottom) T_{dep}=100°C

devices, also shown in **Fig. 9**. This means that good Vth-matching can be achieved by the PVD-Si precursor for CMOS process flow.

Fig. 10 shows p-Si TFT characteristics as a function of the process conditions used for the deposition of the PVD-Si precursor film. The TFT performance improves at lower sputtering pressure, but it seems that an optimum pressure setting exists, which depends upon the substrate temperature5). This optimum is found around 2.5-4mTorr at 400°C and drops even lower at 100°C. The existence of this optimum, most likely relates to the microstructure of the as-sputtered film and its dependency on the process parameters shown in **Fig. 10**.

Conclusions

In this paper we have reviewed Si-sputtering technology for application in p-Si TFT-LCDs. Sputtering can be used to deposit a-Si films, which are subsequently crystallized, most commonly, by application of excimer-laser annealing. We reviewed the characteristics of PVD a-Si films and identified operating conditions that yield high quality films. Sputtering can deposit Si-films at temperatures as low as RT, which makes this technology advantageous for application to temperature sensitive substrates, such as plastics.
It is clear now that by optimization of the as-sputtered material and the crystallization process, high quality p-Si films can be obtained. Poly-Si TFTs fabricated with this material show promising characteristics even at very low fabrication temperatures. The TFT flow, however, needs to be considered in the optimization process. Other steps, such as gate dielectric deposition, doping, activation and hydrogenation have also to be optimized for the PVD-Si precursor.

One of the issues of sputtering technology is particle generation and one way to overcome it is the use of RF technology. However, RF sputtering tends to yield low deposition rates, which are not compatible with mass production requirements. Furthermore, RF technology is more complex and more expensive than DC technology. Smart equipment design is also necessary to overcome the problems of disappearing anode, metal contamination and particles. Most importantly, currently there is no mass production equipment commercially available for Si-sputtering. Hence, a number of challenges remain before PVD can become a mainstream technology for Si and Si-dielectric film deposition.

As the LCD industry moves to poly-Si technology, more consideration will be given to the advantages offered by PVD technology. Looking further ahead, film processing on transparent flexible substrates is very difficult to achieve by current technology due to the severe temperature limitation of cheap plastics. Hence, sputtering seems to be one of the few viable technologies that can help close this gap.

Acknowledgments
The authors would like to thank the members of SHARP’s Tenri LCD Laboratories for their technical support.

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(received May 24, 2001)