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Properties of n^+ and p^+ polysilicon thin films fabricated by an excimer laser-activated spin-on dopant technique

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Abstract

Shallow n^+ and p^+ junctions have been fabricated using a 'spin-on' dopant introduced into the material and activated by irradiation with a KrF excimer laser. The shape of the doping profile and its variation with the number of laser pulses were measured using secondary ion mass spectrometry (SIMS). For n^+ films, the Hall mobility and the height of the grain boundary potential barrier were measured as a function of both laser fluence and number of pulses. The maximum electron mobility was 16 $cm^2\ V^{-1}\ s^{-1}$, while the minimum barrier height for carrier transport was 2.14 meV. The maximum dc conductivity was 74 S cm^{-1}, making the doped material useful for the formation of high-quality source and drain regions in amorphous silicon thin film transistors.

Keywords: Polycrystalline silicon; Laser crystallisation; Hall effect; Secondary Ion Mass Spectrometry (SIMS); Thin film transistors; Laser-induced doping

1. Introduction

Thin film transistors (TFTs) are key elements of active matrix liquid crystal displays, linear image sensors, printing heads and other systems. Polycrystalline silicon (polysilicon) TFTs (and hydrogenated amorphous silicon (a-Si:H) devices using polycrystalline source and drain regions) [1] require shallow, high concentration doping for source and drain formation. Considerable effort has been devoted to developing fabrication methods such as low energy ion implantation, producing an amorphous state, plasma immersion implantation and thermal diffusion. However, it is often difficult to selectively form good shallow doped regions using low-energy sources. Additionally, long-term thermal processing is often incompatible with glass substrates and detrimental to gate insulator quality.

Since KrF 248 nm excimer laser radiation is absorbed by amorphous silicon, it is possible to melt the surface region, permitting efficient dopant diffusion to occur. The process features minimal thermal interaction with the substrate, which may thus be a glass with a low melting temperature. Results have been reported by various researchers (e.g., Refs. [1–4]). The aim of this section was to investigate the dopant depth profile, Hall mobility and active carrier concentration of n^+ and p^+ polysilicon films fabricated by KrF excimer laser induced crystallisation of amorphous silicon, with simultaneous doping from the irradiated surface using phosphorus and boron

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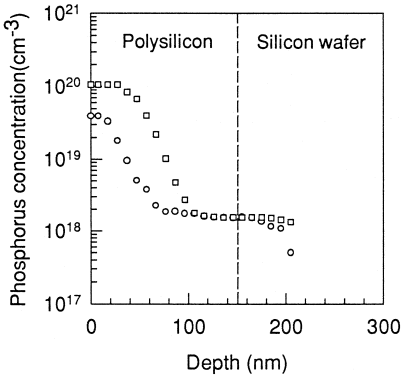

Fig. 1. Phosphorus concentration depth profiles for n^+-polysilicon films doped at a laser fluence of 175 mJ cm^{-2}, using (a) 40 pulses, and (b) 600 pulses. The dotted line indicates the depth of the crystallised region.

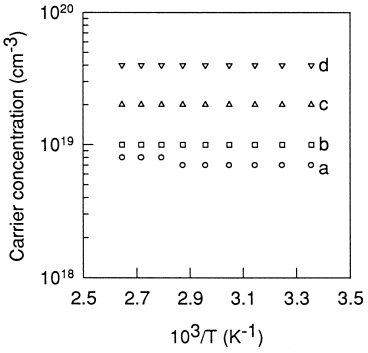

Fig. 3. Carrier concentration as a function of inverse temperature for phosphorus-doped polysilicon films, irradiated at a laser fluence of 175 mJ cm^{-2} using (a) 40 pulses, (b) 80 pulses, (c) 120 pulses, and (d) 240 pulses.

spin-on coatings [1,4]. As we shall show, the method is very effective.

2. Experimental details

2.1. Sample fabrication

Undoped a-Si:H films, 150 nm thick, were deposited on glass (Corning 7059) for Hall effect measurements and on intrinsic polished crystalline silicon wafers for secondary ion mass spectrometry (SIMS) measurements, using a conventional plasma enhanced chemical vapor deposition (PECVD) reactor operating at 13.56 MHz. Deposition was at a SiH_4 flow rate of 25 sccm, a chamber pressure of 0.5 Torr, an r.f. power density of 80 mW cm^{-2} and a substrate temperature of 250°C. For laser-assisted doping, emulsions (P509 and B155, Filmtronics) containing phosphorus and boron at concentrations of 2×10^{21} and 5×10^{20} atoms cm^{-3}, respectively were deposited on the surface of the a-Si:H by spin coating. The samples were baked at 200°C for 2 h, giving dopant layers 200 nm thick. Laser induced crystallisation and dopant incorporation were carried out simultaneously in air, using a KrF excimer laser (LPX-105 Lambda Physik) providing large area (up to 6 mm $\times$ 20 mm) pulses of 17 ns duration. Use of varying laser repetition rates (1 to 30 Hz) allowed a selectable number of pulses to be directed to any given location. The processed area was scanned by moving the sample along the long axis of the laser

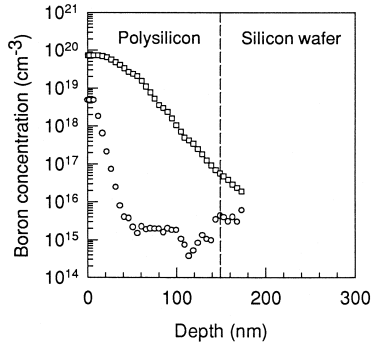

Fig. 2. Boron concentration depth profiles for p^+-polysilicon films doped at a laser fluence of 175 mJ cm^{-2} using (a) 120 pulses, and (b) 600 pulses. The dotted line indicates the depth of the crystallised region.

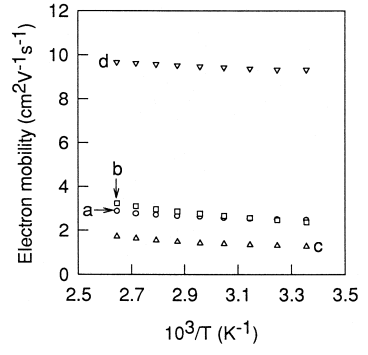

Fig. 4. Electron Hall mobility as a function of inverse temperature for the phosphorus-doped polysilicon films identified in Fig. 3.

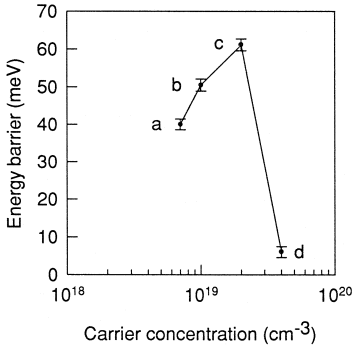

Fig. 5. Energy barrier height as a function of carrier concentration for the phosphorus-doped polysilicon films identified in Fig. 3. The solid line is provided as a guide to the eye.

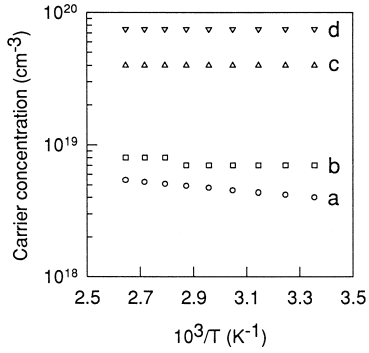

Fig. 7. Carrier concentration as a function of inverse temperature for the phosphorus-doped polysilicon films identified in Fig. 6.

beam at a rate of 0.5 mm s^{-1}. This diminished effects of beam inhomogeneity and allowed the establishment of a continuous crystallised region. Where required, as for the fabrication of doped source and drain regions in TFTs, a simple masking technique using a patterned silicon nitride overlayer has been developed [1] to allow confinement of crystallisation and doping to the desired regions.

2.2. Hall effect measurements

The Van der Pauw technique, using aluminium electrodes, was employed for Hall effect and resistivity measurements, to estimate the average carrier concentration and mobility of the doped films. Measurements were made in a light-tight chamber at magnetic fields up to 0.75 T. Samples were mounted on a Peltier effect heat pump, allowing temperature control to within ± 0.5 K.

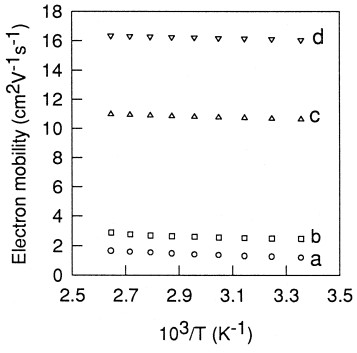

Fig. 6. Electron mobility as a function of inverse temperature for phosphorus-doped polysilicon films irradiated with 40 pulses at different laser fluences: (a) 155 mJ cm^{-2} ($E_a = 41.14$ meV), (b) 175 mJ cm^{-2} ($E_a = 39$ meV), (c) 215 mJ cm^{-2} ($E_a = 4.75$ meV), and (d) 235 mJ cm^{-2} ($E_a = 2.14$ meV).

3. Results

Dopant impurity concentrations and depth profiles were determined by SIMS, using a spectrometer (IMS CAMECA). Figs. 1 and 2 show data for material doped and crystallised using different numbers of pulses.

Figs. 3 and 4 show the temperature variations of carrier concentration and Hall mobility respectively (averaged over the full thickness of the film), for n-type samples made with different numbers of pulses. The variation of mobility activation energy with average (room temperature) carrier concentration is shown in Fig. 5, while Figs. 6 and 7 show the effects of laser fluence upon electron mobility and carrier concentration.

4. Discussion

4.1. Dopant concentration profile

As in our earlier studies [1], the number of pulses does not change the depth of the recrystallised region (formed largely during the first pulse), but affects the concentration of impurity atoms within it. Prior numerical simulations [5] have calculated a total melt

depth of 70 nm at 200 mJ cm^{-2}, for 193 nm ArF irradiation. This depth is not consistent with our measurements in Figs. 1 and 2, which indicate depths of 150 to 200 nm. Conceivably, the simulation may not take proper account of the amorphous-polycrystalline transition after initial laser irradiation. This transition can involve explosive crystallisation (self-propagating melting). After solidification, the latent heat will be released [6], inducing further melting of the underlying amorphous material. Furthermore, the presence of the spin-on dopant decreases surface reflectivity [7] and also provides thermal insulation during the crystallisation/dopant activation [4]. Consequently, the duration of the molten phase is increased, allowing the dopant to be incorporated deeper into the material.

The factors determining the detailed concentration profiles in Figs. 1 and 2 are complex. When the first pulse melts the amorphous precursor, dopant will be incorporated by a combination of mixing and diffusion. The subsequent recrystallisation will propagate primarily from the substrate upwards, because of the higher efficiency of heat transfer to the substrate than through the free surface. The higher solubility of dopant in the liquid phase will then result in some impurities being redistributed back towards the surface. Subsequent pulses will obviously cause further, primarily diffusion-induced, dopant injection from the surface, and a redistribution of existing impurities within the bulk. Such 'secondary' injection must be substantial, since the total impurity concentration measured by SIMS is increased appreciably when the number of pulses is raised from 40 to 600.

4.2. Hall effect

Fig. 3 shows that the (depth-averaged) carrier concentration in the doped films increases with the number of pulses, as expected from the SIMS data, and is almost constant with temperature. We can thus assume that the intergranular regions believed to dominate transport are effectively saturated with dopant.

The temperature variation of the electron Hall mobility (Fig. 4) is also controlled by potential barriers at the grain boundaries [8]. A maximum in barrier height (Fig. 5) occurs at an average carrier concentration of about 1×10^{19} atoms cm^{-3}. From other studies [8,9] of polysilicon films prepared *under high vacuum* (grain sizes 24 to 60 nm), the maximum occurred at doping levels in the range 5×10^{17} to 5×10^{18} atoms cm^{-3}. Our peak occurs at a higher concentration, despite the larger grain size of 150 nm, probably because of a higher density of trapping centres in the grain boundaries. In the present study, crystallisation/doping was conducted in air, which could possibly cause grain boundaries to be contaminated with oxygen, thus increasing the density of mid-gap states [10]. However, laser processing under vacuum could readily be performed if further studies establish its desirability for practical applications.

Fig. 6 shows that increasing the laser fluence increases the electron Hall mobility, and also slightly decreases the height of the energy barrier (E_a). This effect is related to the variation in the grain size with irradiation intensity [11]. With increasing grain size, the trap activation energy remains approximately constant while the trap density decreases [9].

Raising the laser fluence also leads to an increase in average carrier concentration (Fig. 7). The time during which the layer is molten increases, and the molten zone becomes deeper. Consequently, more dopant is incorporated [1]. Fig. 7 also shows that the carrier concentration in polysilicon doped at a laser fluence of 155 mJ cm^{-2} or more does not vary, within errors of measurement, with temperature, confirming that the intergranular regions become saturated at an average carrier concentration of around 10^{19} cm^{-3}.

The maximum room temperature d.c. conductivity obtained for our doped films was 74 S cm^{-1}, making the materials very attractive for device applications, such as the formation of high-quality source and drain regions in amorphous silicon thin film transistors.

5. Conclusions

The laser irradiation causes the a-Si:H to crystallise and the dopant to diffuse in simultaneously. By changing the laser fluence and the number of pulses, the Hall mobility, the average carrier concentration, and the height of the intergranular energy barriers can be controlled. SIMS analysis shows a depth of the doped region of about 150 nm for both boron and phosphorus doped films. The average

dopant concentration can be readily controlled by varying the number of pulses. Both laser crystallisation and doping from a spin-on source appear very promising as replacements for standard technologies in the fabrication of high-concentration shallow junctions for narrow channel thin film transistors. Particularly with the inclusion of a patterned overlayer to allow selective crystallisation and doping [1], the process offers simplicity and versatility of operation without the need for sophisticated equipment.

References

[1] E. Al-Nuaimy, J.M. Marshall, Appl. Phys. Lett. 69 (1996) 3857.
[2] K. Sera, F. Okumura, S. Kaneko, S. Itoh, K. Hotta, H. Hoshino, J. Appl. Phys. 67 (1990) 2359.
[3] E. Fogarassy, H. Pattyn, M. Elliq, A. Slaoui, B. Prevot, R. Stuck, S. de Unamuno, E.L. Mathe, Appl. Surf. Sci. 69 (1993) 231.
[4] E.A. Al-Nuaimy, J.M. Marshall, T.E. Dyer, A.R. Hepburn, J.F. Davies, in: J.M. Marshall, N. Kirov, A. Vavrek (Eds.), Proceedings of the 8th International School on Condensed Matter Physics, Research Studies Press, 1995, p. 712.
[5] S. de Unamuno, E. Fogarassy, Appl. Surf. Sci. 36 (1989) 1.
[6] T. Sameshima, S. Usui, J. Appl. Phys. 70 (1991) 1281.
[7] T. Sameshima, S. Usui, Jpn. J. Appl. Phys. 26 (1987) 1208.
[8] J.Y.W. Seto, J. Appl. Phys. 46 (1975) 5247.
[9] N.C.C. Lu, L. Gerzberg, C.Y. Yu, J.D. Meindl, IEEE Trans. Electron. Devices E 28 (1981) 818.
[10] H.J. Queisser, J.H. Werner, Mater. Res. Soc. Symp. Proc. 336 (1994) 835.
[11] J.S. Im, H.J. Kim, Appl. Phys. Lett. 63 (1993) 1969.