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Low-cost, High Efficiency Solar Cells on Scrapped CMOS Silicon

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ABSTRACT

Silicon wafers scrapped from CMOS production lines were used in this work. The low cost of these wafers make them attractive for photovoltaic applications. However, only modest conversion efficiencies (< 9 %) are obtained from solar cells fabricated on scrapped wafers, primarily due to their very low recombination minority carrier lifetimes (usually < 1 μs). This paper shows that x400 improvement in lifetime of scrapped Si can be achieved via high temperature annealing. The efficiency of cells fabricated on HTA scrapped wafers showed a pronounced improvement to ~ 15%.

INTRODUCTION

In an October 30, 2007 press release [1] IBM announced the development of a new reclamation process allowing scrapped Si wafers to be used as process monitors for CMOS lines as well as starting material for single crystal Si solar cells. It was estimated that ~ 13.5 MW of power could be generated from ~ 3 million Si wafers that are scrapped annually from CMOS production lines worldwide. Though this energy is only a fraction of the present demand, it nevertheless represents a non-negligible energy saving and environment preservation. However, the cost benefit of scrapped wafers is offset by modest efficiencies that are typically obtained from Si solar cells (9 %) fabricated on such wafers. Low conversion efficiencies are a consequence of the poor minority carrier recombination lifetime (< 1 μs).

The present publication reports a low-cost, high temperature anneal (HTA) process which improves the lifetime in scrapped Si wafers by x400. It is believed that chlorine-containing atmosphere during HTA getters metallic contamination (via formation of volatile metal chlorides) [2-3], dissolve oxide precipitates, and annealing out crystal defects in the Si [4] allowing the observed improvement.

EXPERIMENTAL DETAILS

200 mm scrapped Si wafers of 10 Ω.cm resistivity were selected to fabricate solar cells. The wafers underwent etching in tetra methyl ammonium hydroxide (TMAH) at 80 °C to remove ≅ 30 μm thick mechanically damaged surface layer followed by standard RCA cleaning prior to HTA. Typical anneal was conducted at 1200 °C for 17 h or at 1325 °C for 10 h.

The effect of the HTA on scrapped wafer lifetime was monitored by photoconductive decay (PCD) s using a photoconductance lifetime tester model WCT-120, from Sinton Consulting, Inc. The PCD measurements were carried out with wafer surfaces passivated by the oxide grown during the HTA.

Solar cells with a double ("selective") emitter structure were fabricated on both annealed and unannealed scrapped wafers using the following process steps:

1) Surface etching of $\cong 30$ μm of mechanically damaged Si by TMAH
2) Boron ion implantation in back surface
3) Front surface doping with phosphorus using P509 (Filmtronics) spin-on-dopant
4) Phosphorus drive-in to obtain sheet resistance (R_s) of 15 Ω/□
5) Cell isolation from neighboring Si by mesa structure via reactive ion etch
6) TMAH etching to obtain R_s of 200 Ω/□ in the selective emitter non-contact regions
7) Emitter passivation by dry oxidation
8) Deposition of antireflection coating (ARC) by PECVD of Si_3N_4 and SiO_2
9) Formation of emitter contact using Ti/Pd/Ag
10) Forming gas annealing
11) Formation of base contact by Au metallization
12) Cu plating of fingers and bus-bar

The fabricated solar cells were characterized by current density (J) versus voltage (V) measurements in the dark and under illumination with intensity of 1.0 sun at AM1.5 spectrum and external quantum efficiency (EQE) measurement. The cell area was 1.0 cm^2 defined by a mesa etch. For J versus V measurement under illumination, the regions outside the cell were masked by an opaque mask having an aperture equal to the area of the cell.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show lifetime versus minority carrier concentration extracted from PCD measurements in scrapped wafers after HTA conducted at 1200 ^{o}C for 17 h and 1325 ^{o}C for 10 h, respectively. Included in Fig. 1(b) is the data from control monitors with the original damaged surface with and without HTA. The surfaces of the monitor wafer were passivated by HF etching just before the PCD measurement.

It is clear from the data in figures 1(a) and 1(b) that maximum lifetime improvement of x400 occurs after HTA when surface damage layer is removed and highest anneal temperature (i.e., 1325 ^{o}C) is used. Such HTA-lifetime improvement dependence indicates that this is a high activation energy process. It is interesting to note that lifetime improvement is nearly independent of anneal temperature in samples with the original damaged surface.

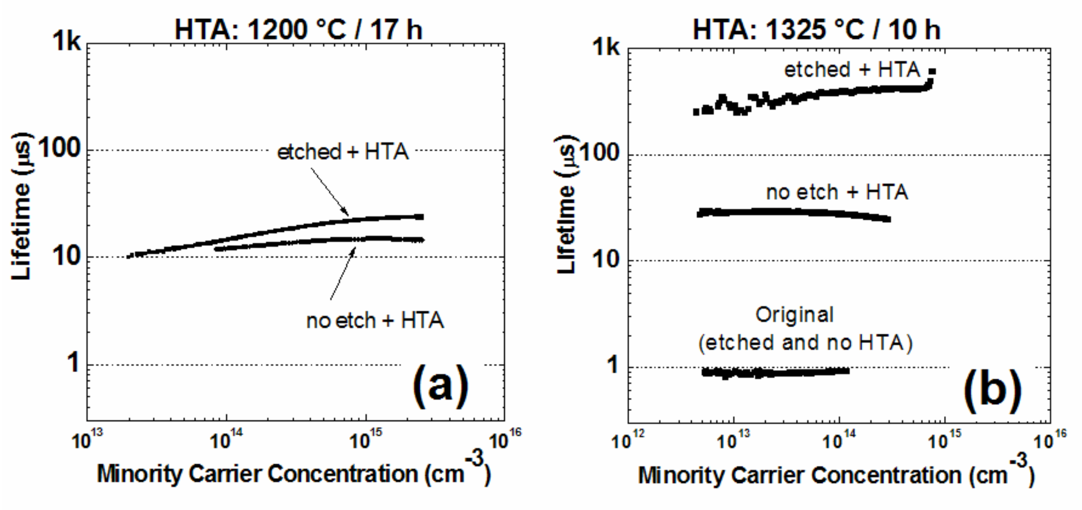

Figure 1. Lifetime as a function of the minority carrier concentration (PCD measurements) after HTA (a) at 1200 °C for 17 h and (b) at1325 °C for 10 h.

Figure 2 shows EQE from solar cells fabricated in wafer with no HTA treatment [curve (a)] and with HTA at 1325 °C [curve (b)]. Curve (a) denotes very modest conversion efficiency at all the wavelengths, due to very low lifetime (< 1µs) of the starting scrapped-Si.

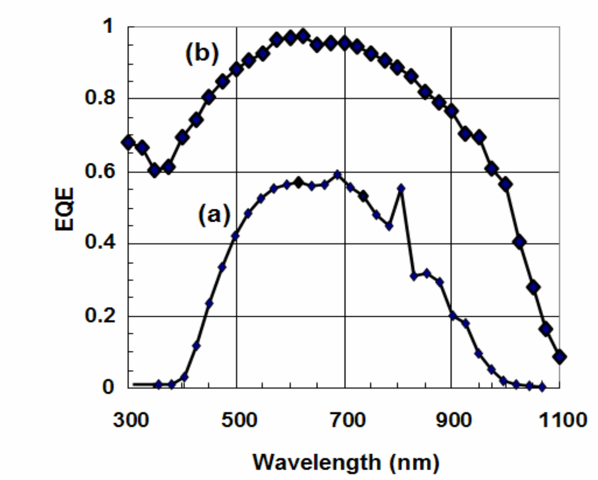

Figure 2 External quantum efficiency measured in solar cell from a control wafer (no HTA) [curve (a)] and from a cell in wafer HTA at 1325 °C for 10 h [curve (b)]. The spike in curve (a) is a measurement artifact.

Curve (b) on the other hand shows a remarkable improvement in conversion efficiency at all wavelengths, which is consistent with high lifetime in the HTA treated wafer. Similarly, decay of EQE at wavelengths above 700 nm is in curve (a) is consistent with the lower lifetime (0.70 µs) of the material. Other factors which also contribute to the decay of EQE at long wavelengths are the ARC reflectance (≅ 10 % at 900 nm) and the lack of a proper back surface field structure. The reduction of EQE at short wavelengths (< 500 nm) is mainly attributable to the relatively high reflectance of ARC which reaches ≅ 40 % at 400 nm.

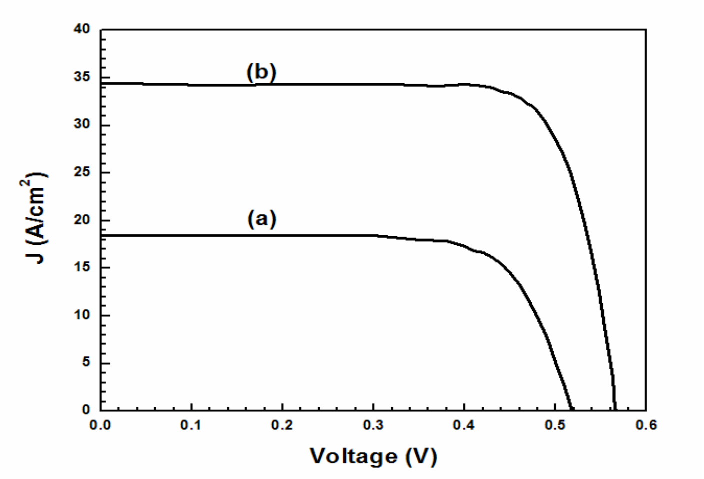

Figure 3 Current density as a function of the voltage measured under illumination with intensity of 1.0 sun (AM1.5 spectrum) in solar cells fabricated in wafers without HTA [curve (a)] and with HTA treatment at 1325 °C for 10 h [curve (b)].

The J versus V characteristics for cells from a control wafer (no HTA) [curve (a)] and a HTA treated wafer [curve (b)] are shown in figure 3 under 1 sun illumination. The photovoltaic conversion efficiencies are 7% [curve (a)] and 15.2 % [curve (b)]. The higher conversion efficiency in the HTA cell correlates with the higher lifetime compared to the untreated cell.

CONCLUSIONS

It is shown that Si solar cells made from scrapped Si from CMOS production can be improved by HTA. It is believed that an oxidizing annealing at temperatures ≥ 1200 ^{o}C in HCl-containing ambient getters metallic impurities and dissolves SiO_x precipitates in scrapped Si to improve its lifetime. A factor of x400 improvement in lifetime and increase in solar cell efficiency from 7 to 15% is demonstrated.

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