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Improvement of Silicon Diode Characteristics by Annealing with Q-Switched Nd:YAG Laser

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***Abstract*—In this work, treatment of defects arising from conventional (classical) thermal annealing, electrical characteristics and dynamic resistance of silicon diode has been carried out by using Q-switched Nd:YAG laser (1064 nm) with energy pulse of 1000 mj with repetition rate of 3,4 and 5 Hz, respectively. Results obtained from the I-V characteristics of silicon diode showed improvement in curve behavior, and the dynamic resistance calculated by graphical analysis based on diode I-V characteristic showed decrease in its value with increasing in pulse repetition rate. The Scanning Electron Microscope (SEM) images showed also reduction of defects on silicon diode surface after laser annealing.**

Keywords—laser in engineering; annealing by lasers; Nd – YAG in industry; annealing of silicon diode.

I - INTRODUCTION

The annealing of semiconductors is an integral part of electronic device fabrication technology. Applications range from the recrystallisation of lattice damage produced by ion implantation to the promotion of chemical reactions such as oxidation or the formation of metal-semiconductor compounds. Heat treatment timescales have generally been those available by use of conventional furnace systems, which limit minimum process times to a significant fraction of an hour [1].

Annealing of amorphous and poly-crystalline Silicon is of interest for recovering surfaces damaged by ion implantation [2]. The ion implantation into crystalline silicon leaves this material highly damaged so that it becomes improper for electronic applications unless an adequate annealing process restores to a high degree the original crystallinity. Depending on the energy, mass, and dose of the bombarding ion, the implanted surface can be rendered amorphous [3].

Ion implantation produces damage to single crystal silicon through lattice displacements by energy transfer to the lattice atoms from the primary ion or from recoiled ions during the implantation. Lattice displacements occur when the energy transferred to a lattice atom through nuclear collisions exceeds 15 eV [4]. This progression of lattice displacements along the path of the ion through the crystal is referred to as the collision cascade. Displacement of a lattice atom produces both an interstitial and a vacancy, called a Frenkel pair. During the relaxation of the collision cascade, many of the Frenkel pairs recombine. The probability of recombination is proportional to the separation distance of the interstitial and vacancy, temperature, and the existence of point defect traps [4]. After recombination of interstitials and vacancies during the relaxation of the collision cascade, a fraction of the Frenkel pairs remain. The number of interstitials and vacancies that remain after ion implantation is a function of the implant conditions including ion mass, ion dose, wafer temperature, and ion dose rate. Upon annealing, an array of different defects can arise depending on the as implanted state of the silicon [4]. The three possible as-implanted morphologies include 1) a damaged (potentially including isolated amorphous pockets) crystalline silicon lattice; 2) the formation of a continuous buried amorphous layer centered around the peak of the damage profile with crystalline silicon above and below the amorphous layer; or 3) an amorphous layer that is continuous from the surface down to a depth determined by the implant conditions. If no continuous amorphous layer is present, then upon annealing most interstitial/vacancy (I-V) recombination occurs at relatively low temperatures (<500°C). If an amorphous layer is formed, then upon annealing this layer will recrystallize by solid phase epitaxial regrowth, typically between 550°C and 650°C. [4]. It is known that high dose implantation-induced defects can act as a nucleation site for the formation and evolution of defects during post-implantation processing. High-temperature annealing, and in particular, rapid thermal annealing, is routinely adopted in semiconductor processing to achieve dopant activation and damage removal while leaving unwanted diffusion [5]. Laser annealing of semiconductor can provide a good alternative for furnace annealing. Nd:YAG laser is used, because this laser is widely used in thermal annealing processes for the semiconductor to reduce and eliminate defects arising through conventional (classical) annealing to improve the diffusivity of impurities and improve the atomic structure of a semiconductor material.

This work aimed to use annealing by Q-switched Nd:YAG laser to treat the defects of silicon diode and to enhance its characteristics and dynamic resistance.

II – MATERIALS AND METHODS

Table (1) and (2) shows the type and specifications of laser and materials used in this work. The materials used in this work are 4 samples of silicon diode, and these samples were an as follows:

TABLE I: Nd:YAG laser type and specifications

Country	China
Company	Shanghai Apolo Medical Technology
Model	HS-220E
Laser Type	Q-Switched Nd: YAG
Wavelength	1064 & 532 nm
Pulse Energy	500 & 1000 mJ
Pulse Repetition Rate	1Hz, 2Hz, 3Hz, 4Hz, 5Hz
Width of Pulse	<10 ns
Spot Diameter	2-8 mm
YAG	¢ 7

TABLE II: Silicon diode parameters

Parameters	Symbol	Maximum Rating	Unit
Maximum repetitive peak reverse voltage	V_{RRM}	50	V
Maximum RMS voltage	V_{RMS}	35	V
Maximum DC blocking voltage	V_{DC}	50	V

First: The samples were irradiated by the Q-switched Nd: YAG laser with wavelength of 1064 nm and energy of 1000 mj with frequency of 3, 4 and 5 Hz, respectively, and then the samples were placed into a sputter coater to cover samples with a thin layer of gold. A conductive coating is needed to prevent charging of a sample with an electron beam in conventional Scanning Electron Microscope (SEM) mode (high vacuum, high voltage).

Second: The samples were placed into a scanning electron microscope to take images of the area before and after irradiation by the Nd:YAG laser (λ=1064 nm).

III – RESULTS AND DISCUSSION

Figure (1-a) shows the defects on the surface of the silicon diode, that are associated with imperfect re-growth of an amorphous layer and are located in the region of the previously amorphous Si. These defects were tentatively associated with residual, buried implantation damage. The main types are hairpin dislocations, microtwins and segregation defects. Hairpin dislocations nucleate when the regrowing a/c interface encounters small microcrystalline regions that are slightly misorientated with respect to the bulk crystalline material. As the microcrystalline pocket is incorporated into the single crystal bulk, a hairpin dislocation is nucleated which propagates to the surface [6,7].

The semiconductors in (b), (c), and (d) from figure (1) were subjected to a single-pulse irradiation with energy of 1000 mj and repetition rate of 3, 4, and 5 Hz, respectively. From Scanning Electron Microscope (SEM), it can be observed that the surface defects are decreased gradually according to increase of laser pulse repetition rate from 3 to 5 Hz. This could be discussed as follows:

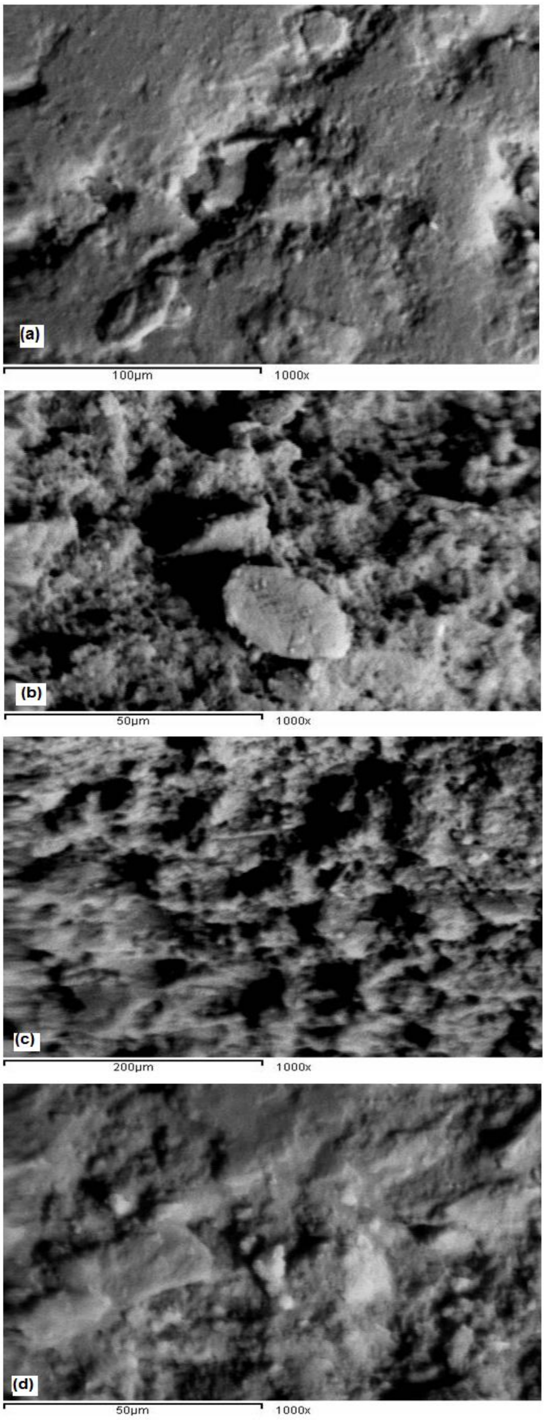

FIGURE I: Scanning Electron Microscope (X1000) images: (a) before annealing (b) after annealing by Nd:YAG laser with 1000 mJ, 3Hz (c) 1000 mJ, 4Hz (d) 1000 mJ, 5Hz

From figure (1-b), the laser fluence is only slightly greater than the threshold fluence for melting a-Si. In this case, the primary melt (molten layer produced directly by laser irradiation) does not penetrate through the entire a-Si layer. Typically, large-grained (LG) polycrystalline silicon (poly-Si) will be formed near the surface region followed by fine-grained (FG) poly-Si in the underlying region (Fig. (2-b)). The fraction of the LG region increase at the expense of FG region with increasing fluence – a result of explosive crystallization [8].

The image (c) in the figure (1), the laser energy of 1000 mJ with repletion rate of 4 Hz is just sufficient for the primary melt of the front to reach the a/c interface without melting the underlying c-Si substrate (Fig. (2-c)). Single-crystalline silicon is thus formed via liquid phase epitaxy (LPE), using the underlying substrate as a template [7].

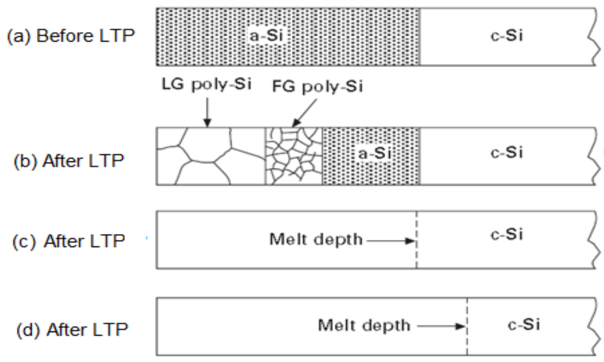

FIGURE II: the structural changes induced by laser irradiation of an a-Si over-layer on c-Si [7]

In theory, this regrowth process should produce crystals with reasonably good quality, however, it has been reported that residual defects such as microtwins and stacking faults exist in the crystallized layer. At higher energy density, figure (1 - d), the primary melt front penetrates beyond the amorphous/crystalline (a/c) interface (Fig. 2- d). In this case, single-crystalline silicon is also formed upon solidification. The melting of a part of the crystalline substrate adjacent to the amorphous layer ensures the epitaxial growth of a nearly defectfree crystal with minimum “quenched-in” interstitials [8].

Figure 3 shows the room-temperature forward current-voltage characteristics of the samples. From this figure the samples irradiated by 1000 mj with 4 and 5 Hz repetition rate, exhibit a turn-on voltage of 0.64 V at 10 mA. This figure also reveals that the forward voltages are 0.7 V at 20 mA dc current for samples (c) and (d) in figure (1), respectively. This could be attributed to the improvement in the surface structure and dopant activation. Figure 4 shows the change in dynamic resistance with repetition rate when the samples were irradiated by a single-pulse from a Q-switched Nd:YAG laser. It is observed that the dynamic resistance decreases as repetition rate increases, indicating an increase in dopant activation and possibly an increase in junction depth with increasing repetition rate. The high degree of dopant activation is attributed to dopant atoms exclusively occupy substitutional lattice sites following laser annealing and the extremely high heating and quenching rates of the laser. As a consequence, the dopants are engulfed in the substitutional sites during crystallization (solute trapping) [8,9].

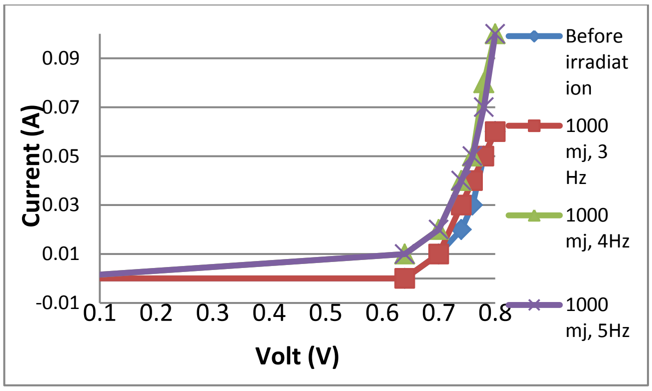

FIGURE III: I-V characteristics of samples irradiated with different frequencies by Nd:YAG laser

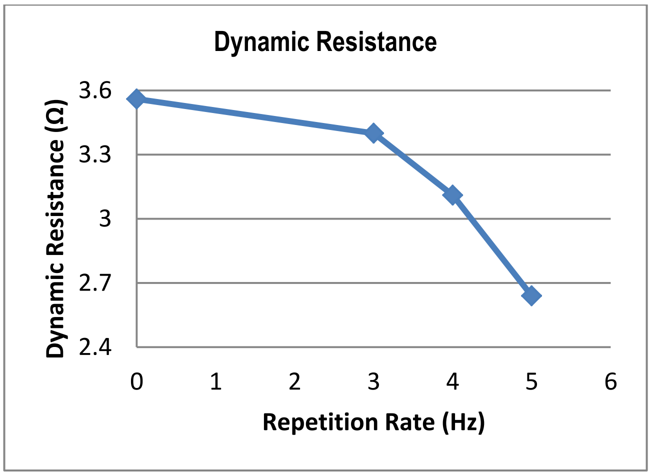

FIGURE IV: The change of dynamic resistance of the samples with repetition rate

IV - CONCLUSIONS

It can be concluded that the defects of silicon diode arising from conventional annealing were decreased via laser annealing and the electrical properties such as I-V characteristics and dynamic resistance were improved after laser irradiation.

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