Normalized Characteristics of Laser-Induced Diffusion of Arsenic Dopants in Silicon

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Abstract

In this work, normalized characteristics of laser-induced diffusion of arsenic in silicon are presented. These characteristics are considered as are enhancing the As-doped silicon-based devices. This enhancement is attributed to the increasing in the diffusion length within a certain layer of the active region in the device. Laser-induced diffusion is a perfect technique for improving the characteristics of electronic devices because it is flexible, contactless, clean and well controlled.

Keywords: Laser-induced diffusion, Arsenic-doped silicon, Transistor current gain

الخلاصة

للانتشار المحتث بالليزر لشوائب الــزرنيخالخصائص المقومةفي هذا البحث، جرى تقديم
الخصائص في محاولة تحسين خصائص النبائط المصنعة منفي السيليكون . يمكن اعتماد هذه
إلى الزيادة المتحققة في طولالخصائصالسيليكون المشوّب بالزرنيخ . يعزى هذا التحسن في .
تعد تقنية الانتشار المحتثالانتشار خلال طبقة محددة من المنطقة الفعالة في مثل هذه النبائط
بالليزر تقنية مثالية لتحسين خصائص النبائط الإلكترونية لأنها تتم بشكل مرن وبدون تماس ما
بين الآلة والعينة كما أنها نظيفة من حيث مخلفات العمل ويمكن التحكم بها بشكل جيد.

1. Introduction

Employment of lasers in microelectronics fabrication and production is one of the most important fields of laser applications which received attention of academic and industrial works during the three last decades. First, lasers are used for annealing of materials in a manner which does not cause damage to the lattice after performance of ion implantation technique. Due to precise control of laser parameters, formation of extremely shallow junctions and redistribution of impurities in semiconductors have become very flexible and reliable techniques compared to the conventional ones [1-12].

Tending toward reducing the geometrical dimensions of electronic and integrated devices to improve their speed and power performance pushed photolithographic resolution to the limits regarding to horizontal dimensions. moreover, vertical dimensions should be reduced to maintain device depths and more closely controlled dopant profiles. Normal thermal diffusion of shallow junctions requires one minute or little less for a typical dopant source. Raising the temperature of a semiconductor wafer to diffusion

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temperatures definitely causes some mechanical problems such as deformations in the solid structure. Such problems should be expected to cause variations in junction dimensions, which is forbidden in manufacturing and fabrication procedures especially when these variations degrade the requirements from such processes [1, 13-14].

Laser-induced diffusion (LID) offers excellent technique for fabrication of the shallow junctions. The heating and cooling rates of semiconductors by LID are (10^{10}-10^{12})°C/s and such rates are sufficient for impurity atoms to occupy substitutional sites in the substrate lattice. Such rates do not admit diffusion to longer distances, thus LID technique provides very sharp diffusion profiles. Laser-induced diffusion technique has an advantage over all conventional techniques as it is performed without masks. Instead, use of optics for focusing laser beam with respect to the surface processed is perfect alternative [2].

As confirmed by recent works, application of dopant sources to the wafer in order to form junctions is followed by laser irradiation. There are several techniques used for deposition of dopant materials on the wafers such as vacuum evaporation, Si-based doping, spray pyrolysis and coatings. Again, dopants can be provided from the gas phase by using laser pulses for photo-decomposition above the surface of wafer and then another laser pulses to induce the diffusion of dopants into the surface of substrate [10-15].

In conventional IC processing, solid-state diffusion is an isothermal process as the substrate is heated uniformly to high temperatures (900-1300)°C, so that the dopant atoms have sufficient energy to move through the lattice of substrate. Such process is emerging from the gradient in impurity concentrations that induces atoms to flow from the high-concentration regions towards those low [16]. Because laser irradiation is a localized heating process in three dimensions, it results in a localized dopant flow. The diffusion coefficient (*D*) is determined as:

$$D = A\exp(-\frac{E_a}{KT}) \qquad (1)$$

where E_a is the activation energy of dopant atoms, K is Boltzman's constant and T is the temperature. Already, the diffusion depth is a function of depth (x) into surface as:

$$D(x) = D(0)\exp(-ax) \qquad (2)$$

where the exponential term corresponds the normalized diffusion profile *D(x)/D(0)*. Both decay constant (a) and diffusion coefficient *D(0)* are determined empirically.

2. Experimental Part

Substrates of (100) p-type silicon wafers were used as substrates. The dopant materials were arsenic, nickel or titanium of 99.99% purity but only the results of arsenic were discussed due to their clearance. Silicon wafers were cleaned in HF solution, rinsed in deionized water, dried in nitrogen then immediately transferred to vacuum deposition system. The thickness of dopant was ~300nm and the wafers were classified into 3 groups due to dopant material. The samples were kept in a sealed vessel until transferred to be irradiated by laser. They were irradiated in air by 10ms pulses from a JK2000 1.06μm Nd:YAG laser system. The maximum power per laser pulse is 1kW with the TEM_{00} mode. Several optical lenses of different focal lengths were used for controlling laser beam size. The position of sample with respect to the laser beam could be varied by a *xy*-table, so the laser beam could scan the sample precisely.

3. Results and Discussion

As shown in Fig. (1), the normalized diffusivity profile decays exponentially with the distance into the substrate. Such decay corresponds a similar response of the optical absorption characteristics. Both decay constant (a) and the diffusivity at the surface (*D(0)*) should be determined empirically by fitting the obtained data of laser-generated profile. Hence, the flux (Φ) of dopants is given by:

$$\Phi = -\frac{\partial}{\partial x}[D(x).N(x,t)] \qquad (3)$$

Consequently, the doping concentration varying with time can be determined by:

$$\frac{\partial N(x,t)}{\partial t} = \frac{\partial \Phi}{\partial x} = -\frac{\partial}{\partial x}\left\{\frac{\partial}{\partial x}[D(x,t).N(x,t)]\right\} \qquad (4)$$

The last equation was solved numerically using MATLAB software to obtain the profile of doping concentration as a function of junction depth, as shown in Fig. (2).

We intended to introduce the characteristics of impurity diffusion in silicon substrate. As shown in Fig. (3), the concentration of arsenic atoms (C_{As}) diffuse inside silicon substrate increases fast with increasing irradiation laser intensity then tends to be constant with increasing laser intensity. This might be attributed to the limits of solid solubility of arsenic dopant in silicon (~2.25×10^{14} atoms/cm^3). Increasing the irradiation laser intensity would cause to exceed damage threshold of the bulk substrate. So, optimum diffusion of dopants can be achieved below a certain value of irradiation intensity.

To explain how to control the depth of the formed junction by the irradiation laser intensity, the junction depth was determined as a function of laser intensity. Although the increasing of depth is slow with increasing laser intensity, as shown in Fig. (4), it seems to be uniform relation, which is necessary to be considered as a control parameter.

In order to introduce the variation of doping concentration (C_{doping}) along the depth into surface of silicon substrate, we have measured doping concentration with depth for three different irradiation intensities ($I_1<I_2<I_3$). It is obvious from Fig. (5) that doping concentration decreases with advance inside surface as well as the higher irradiation intensity induces dopants to penetrate deeper. This behavior in Fig. (5) agrees well with the normalized diffusivity in Fig. (1).

With respect to Eq. (2) and boundary conditions, we can determine the diffusivity of dopants as a function of irradiation laser intensity. As expected, the diffusivity increases linearly with increasing intensity to the maximum intensity used. The linearity enables to suppose that the profile of arsenic doping is uniform which simplifies the numerical treatment of such variation. Results are shown in Fig. (6). Such increasing cannot be continuous as confirmed by the same equation due to the limitation of decay coefficient (a).

4. Conclusions

Due to results obtained in this work, diffusivity profiles of arsenic dopants in silicon substrate are determined. The diffusion of dopants is induced by irradiation with pulsed laser. Laser-induced diffusion is a perfect technique for improving the characteristics of electronic devices because it is flexible, contactless, clean and well controlled.

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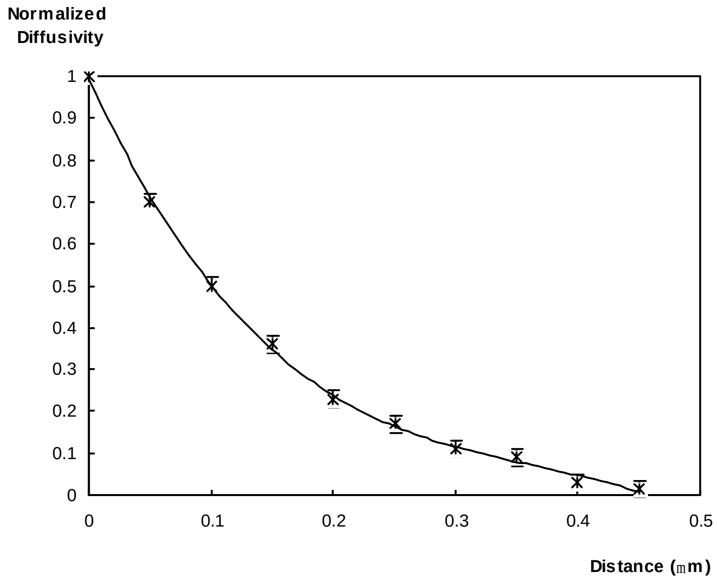

Fig. (1): Normalized diffusivity as a function of distance into the substrate.

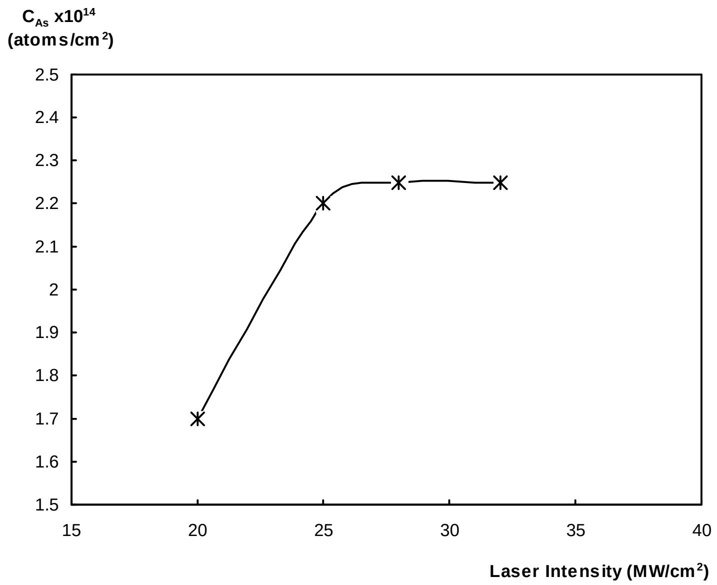

Fig. (2): The concentration of arsenic atoms diffused inside silicon substrate as a function of the irradiation laser intensity. The plateau value is ~2.25x10^{14} atoms/cm^3 of arsenic dopant.

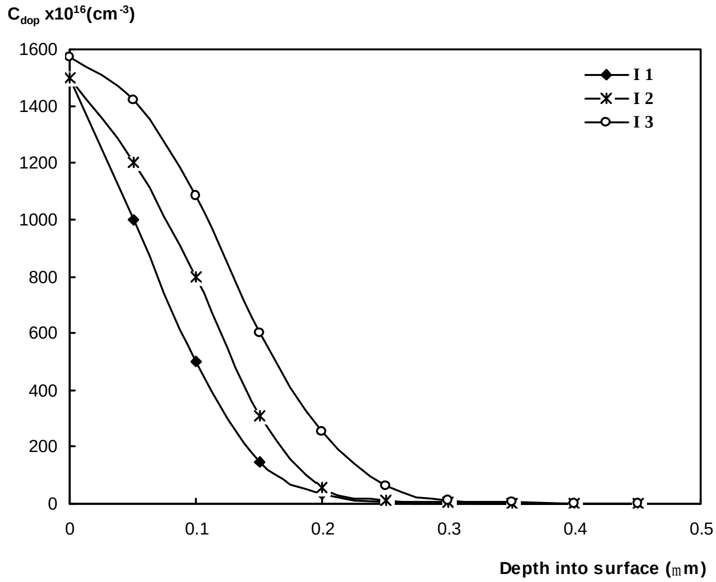

Fig. (3): Doping concentration obtained numerically as a function of the junction depth.

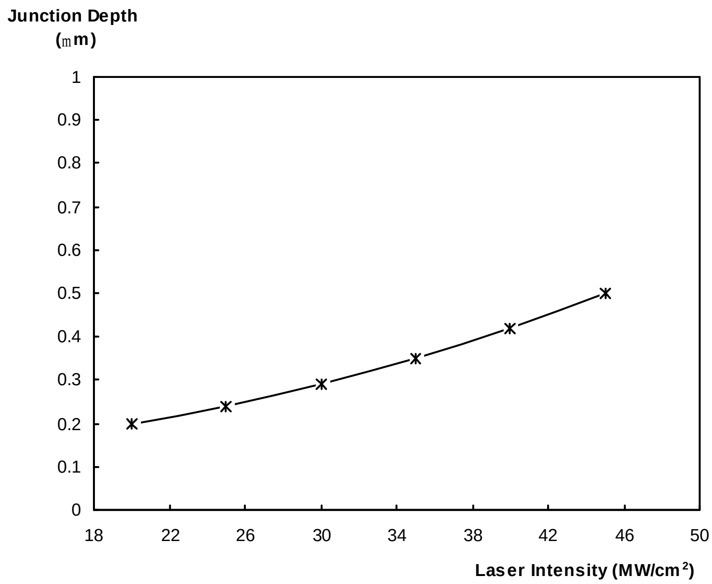

Fig. (4): Depth of the formed junction as a function of laser irradiation intensity.

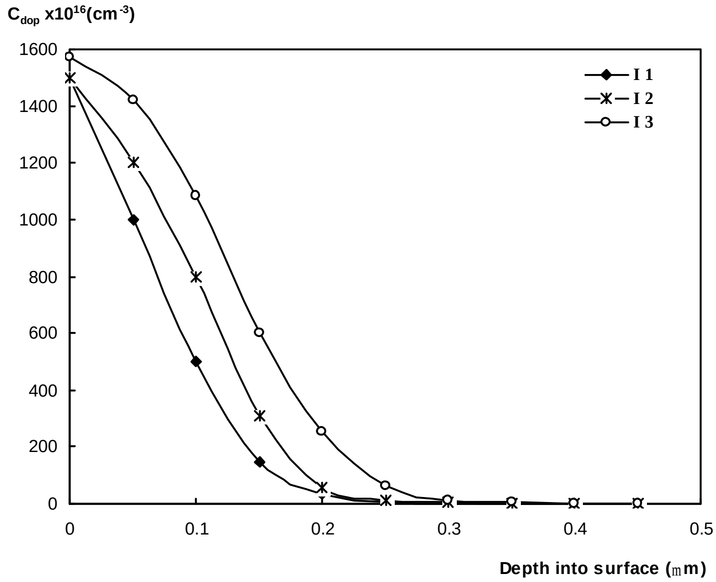

Fig. (5): The concentration of arsenic atoms as a function of depth into surface at three different irradiation laser intensities (10, 20, and 25W/cm^2).

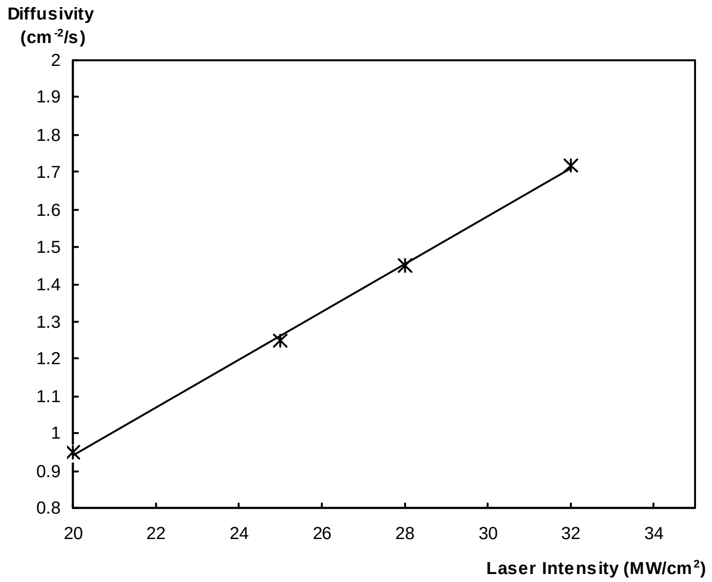

Fig. (6): The laser-induced diffusivity of as a function of laser intensity. Though it is linearly increasing function but it is in fact limited by the solid solubility of dopants.