

Gain Characteristics of Silicon Transistor Treated by Laser

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Abstract

In this work, profiles of laser-induced diffusion of arsenic in silicon are presented. These profiles are considered to attempt increasing of the current gain of silicon transistors. The current gain is well enhanced. This enhancement is attributed to the increase achieved in the diffusion length within a certain layer of emitter region. Laser-induced diffusion is a perfect technique for improving the characteristics of electronic devices since it is flexible, contactless, clean and well controlled.

Keywords: Silicon devices, Laser-induced diffusion, Gain characteristics

الخلاصة

في هذا البحث، جرى تقديم أنماط الانتشار المحتث بالليزر لشوائب الزرنيخ في السيليكون. تم اعتماد هذه الأنماط في محاولة لزيادة ربح التيار للترانزستورات المصنعة من السيليكون، وقد جرى تحسين ربح التيار بشكل جيد. يعزى هذا التحسن في ربح التيار إلى الزيادة المتحققة في طول الانتشار خلال طبقة محددة من منطقة الباعث. تعد تقنية الانتشار المحتث بالليزر مثالية لتحسين خصائص النبائط الإلكترونية إذ أنها تتم بشكل مرن وبدون تماس ما بين الآلة والعينة كما أنها نظيفة من حيث مخلفات العمل ويمكن التحكم بها بشكل جيد.

Introduction

Employment of lasers in microelectronics fabrication and production is one of the most important fields of laser applications. It has received attention of academic and industrial works during the three last decades. First, lasers were used for annealing of materials in a manner 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 became very flexible and reliable techniques compared to the conventional ones [1-11].

Trends are toward reducing the geometrical dimensions of electronic

and integrated devices to improve their speed and power performance. Photolithographic resolution is pushed to the limits regarding 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 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

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procedures especially when these variations degrade the requirements from such processes [1, 12-13].

Laser-induced diffusion (LID) offers excellent technique for fabrication of the shallow junctions. The heating and cooling rates of semiconductors by LID are $(10^{10}-10^{12})^{\circ}\text{C/s}$ and such rates are sufficient for impurity atoms to occupy substitutional sites in the substrate lattice. Such rates do not admit for diffuse 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. Furthermore, 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 [10-14].

In conventional IC processing, solid-state diffusion is an isothermal process as the substrate is heated uniformly to high temperatures $(900-1300)^{\circ}\text{C}$, 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 [15]. 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:

$$D = A \exp\left(-\frac{E_a}{KT}\right) \quad (1)$$

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:

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

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.

Assuming the NPN transistor structure shown in Fig. (1), the current gain (b) of transistor is given as:

$$b = \frac{I_C}{I_B} \quad (3)$$

where I_C and I_B are the collector and base currents, respectively. Often, collector current approximates to emitter current ($I_C \sim I_E$). Hence

$$b \approx \frac{I_E}{I_B} = \frac{qnu_e E}{qnu_h E} \quad (4)$$

where q is electron charge, n is carrier density in each region (electrons in emitter and holes in base region), u_e and u_h are the mobilities of electrons and holes, respectively, and E is the applied electric field. In term of resistance, we get

$$b \approx \frac{I_E}{I_B} = \frac{qnu_e E}{qnu_h E} = \frac{R_B}{R_E} = \frac{r_B \frac{l_B}{A_B}}{r_E \frac{l_E}{A_E}} \quad (5)$$

$$b = \frac{r_B \frac{l}{A_B}}{r_E \frac{l}{A_E}} = \frac{r_B}{r_E} \frac{\frac{l}{x \times y_B}}{\frac{l}{x \times y_E}} = \frac{r_B}{r_E} \frac{y_E}{y_B} \quad (6)$$

since $y_B = x$ then

$$b = \frac{r_B}{r_E} \frac{y_E}{x} \quad (7)$$

Here, y_E is the diffusion length of n-type carrier in the emitter region. Accordingly, the current gain (b) can be changed by only changing the value of y_E because the terms r_E , r_B and x are necessarily constant. The value of diffusion length is related to carrier lifetime as well as carrier concentration diffused inside the bulk. Therefore, the major goal of this study is focused on employing laser-induced diffusion technique to change such parameters.

Experimental

Substrates of (100) p-type silicon wafers were used as substrates. The dopant materials were arsenic, nickel or titanium of (0.9999) purity. 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.

For transistor gain measurements, 6 groups of thin film NPN transistors (assigned as ZTX869, Q2N3904, MPS3704, BC239, BD239 and MPS3904) were used. The values of forward current gain (b) of these transistors are 100, 200, 200, 107, 156 and 782, respectively. The structure of such NPN transistor is shown in Fig. (1) and we assumed to

use it in the common-collector (CC) configuration.

The samples were irradiated in air by a CW CO₂ laser system delivering maximum power of 60W with the TEM₀₀ mode. Several optical lenses of different focal lengths were used for controlling laser beam size and hence laser intensity. The maximum intensity of laser beam is about 10⁵W/cm². 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.

Results and Discussion

First of all, we have intended to introduce the characteristics of impurity diffusion in silicon substrate. As shown in Fig. (2), the concentration of arsenic atoms (C_{As}) diffused 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 solid solubility ($\sim 2.25 \times 10^{14}$ atoms/cm³) of arsenic dopant. Increasing the irradiation laser intensity would cause excessive damage threshold to the bulk substrate.

In order to introduce the variation of doping concentration (C_{dop}) along the depth into surface, we have measured doping concentration with depth for three different irradiation intensities ($I_1 < I_2 < I_3$). It is obvious from Fig. (3) that doping concentration decreases with advance inside surface as well as the higher irradiation intensity induces dopants to penetrate deeper.

With respect to Eq. (2) and the 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. (4). Such increasing cannot be continuous as confirmed by the same equation due to the limitation of decay coefficient (a).

The results of diffusivity and the uniform profile obtained have encouraged the research to apply such principle to the transistor structure in order to enhance one of the important parameters, current gain (b).

Controlling the irradiation laser intensity could control the doping concentration of each of the three regions of transistor structure (emitter, base and collector). As the emitter is the source of carriers and the base is region forming the p-n junction with the emitter, then laser-induced diffusion can be necessarily applied in both regions.

Fig. (5) explains the normalized current gain (b) of the transistors measured as a function of the irradiation laser intensity. Using low intensities results in high and stable gain since the concentration of dopants is increased with laser intensity within a certain layer of surface, as shown in Fig. (2), and this in turn increases the diffusion length of carriers in emitter region (y_E). At higher intensities, the current gain drops clearly because of the resulting increasing in doping depth that leads to decreases the doping concentration, as shown in Fig. (3), despite the corresponding increasing diffusivity. Fig. (6) indicates the enhancement achieved in the groups of transistors.

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. These profiles are attempts aiming to increase the current gain of silicon transistors. Diffusivity profiles confirm that the doping concentration, and hence the diffusion depth, can be increased in the emitter region. This leads to raise the current gain, though the increase in gain has a limit, which is determined mainly by irradiation laser intensity since this intensity should not exceed the damage threshold of substrate. Laser-induced diffusion is a perfect technique for improving the characteristics of electronic devices since it is flexible, contactless, clean and well controlled.

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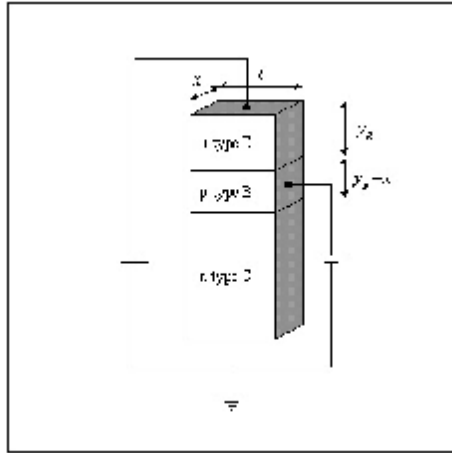


Fig. (1): The structure of such NPN transistor used in this work. It is CC configuration.

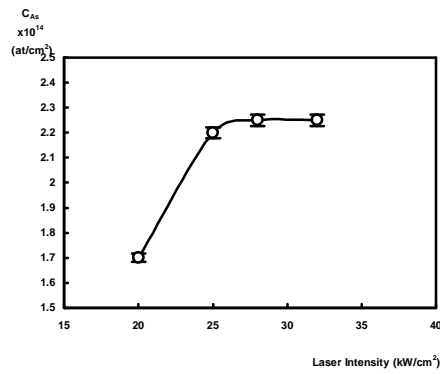


Fig. (2): The concentration of arsenic atoms diffused inside silicon substrate as a function of the irradiation laser intensity. The plateau value is $\sim 2.25 \times 10^{14}$ atoms/cm³ of arsenic dopant.

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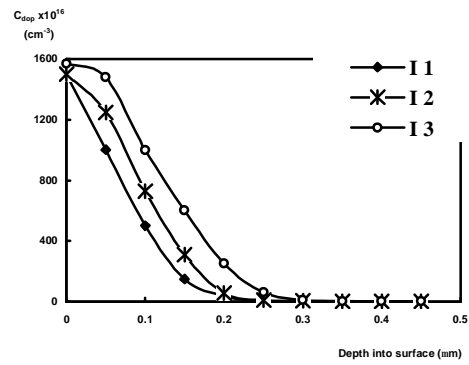


Fig. (3): The concentration of arsenic atoms as a function of depth into surface at three different irradiation laser intensities (10, 25, and 50 kW/cm²).

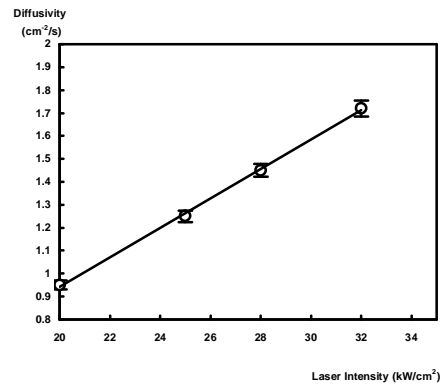


Fig. (4): The laser-induced diffusivity of As as a function of irradiation laser intensity.

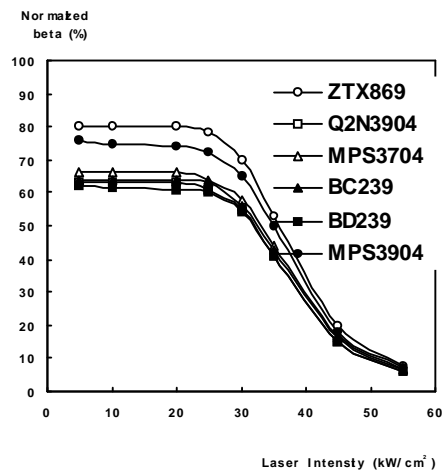


Fig. (5): The normalized current gain (*b*) of the transistors as a function of the irradiation laser intensity. Each point is an average of six readouts using LID technique.

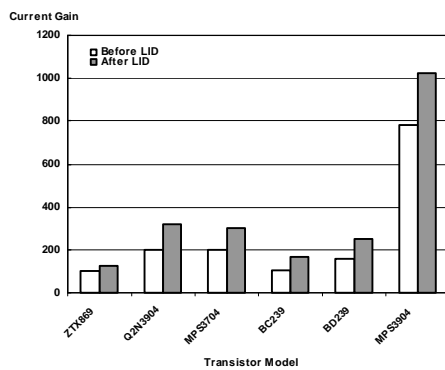


Fig. (6): The enhancement achieved in the groups of transistors using the laser-induced diffusion technique.