Journal of Electron Devices, Vol. 6, 2008, pp. 197-202

© JED [ISSN: 1682 -3427]

Journal of Electron Devices
www.jeldev.org

BJT Fabrication Using Excimer Laser Assisted Spin-on Doping Technique

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received 13-01-2008

ABSTRACT

Excimer laser assisted spin-on doping technique is used to fabricate the base and emitter regions of narrow-base n-p-n bipolar transistors. The Excimer laser assisted spin-on doping technique is unique in that it allows simple fabrication of box-like impurity profile which can be placed very accurately in the vertical dimensions (± 10 nm). Transistors with base widths ranging from 80 to 130 nm and dc forward current gains (β_f) greater than 60 are fabricated.

Index Terms—Spin-on-dopant, laser doping, dopant profile, leakage current, dc forward current gain.

INTRODUCTION

As lateral dimensions in bipolar transistor technologies continue to shrink, reduction in the vertical dimension must also continue if maximum performance gains are to be realized. In particular, the width of the base region must be minimized. Because of channeling tails, shadowing, standard deviation (ΔR_p), and crystal damage, the use of ion implantation to form narrow base regions has become very complex [1]. A popular alternative to implantation is diffusion from doped layers such as polysilicon or oxide [2]. Such methods allow reductions in the base width over those attainable by implantation.

However, the new methods require successive high-temperature diffusions of emitter and base dopants through complex interfacial regions. These diffusions not only increase the thermal budget of the process, they also add to the complexity of an already tedious fabrication sequence. Finally, the successive diffusions remove a degree of freedom in process design by eliminating the independence of emitter and base junction depths.

The laser doping method has been reported to produce superior device characteristics compared with other conventional doping methods [3, 4, 5, 6]. Many different techniques for the formation of heavily doped shallow junctions using laser beams have been explored. Gas immersion laser doping (GILD) [7] and laser induced melting of pre-deposited impurity doping (LIMPID) [8] are the two main methods for doping Si and GaAs; the UV excimer laser has been used predominantly because of its large absorption coefficient in Si and GaAs at UV range. The radiation from the excimer laser is strongly absorbed in the near-surface region of the wafer. Thus, only a shallow depth from the surface can be melted. Furthermore, laser doping can only dope the semiconductor in a selected region, but can also prevent the redistribution of the impurity profile due to its short duration of irradiation.

Although extensive research work has been done on laser induced doping using gas phase molecules as impurity sources [9], there are still only a limited number of papers on laser doping using spin-on dopants (SOD) as impurity source [10]. This method does not require complicated equipment or dangerous toxic gas sources. The requirement for ultrahigh vacuum is also less stringent.

For laser-assisted doping, emulsions (P509 and B155, Filmtronics) containing phosphorous and boron at concentrations of 2×10^{21} and 5×10^{20} atoms cm^{-3}, respectively were used to form solid thin films on n-type silicon <100> surface; this surface was irradiated and the dopant atoms were subsequently incorporated into the sample using KrF excimer laser at various energy fluences and pulse numbers.

THE EXCIMER LASER DOPING TECHNIQUE

The excimer laser assisted spin-on doping technique uses a pulsed excimer laser operating at 248 nm to melt the silicon surface. The incorporation of dopant atoms into crystalline silicon and their electrical activation can be envisaged as follows. First, they are liberated from the coated solid thin film through thermal-assisted dissociation, where laser irradiation was used to heat the sample. Secondly, they undergo rapid diffusion at high temperature into the liquid phase silicon. Solid phase diffusion through the melt/solid interface is only possible for large pulse number. The molten layer regrows epitaxially, resulting in electrically active, damage-free layer. During the ultrafast melt/regrowth process (<200 ns in duration) dopant incorporation is restricted to the liquid phase. This limits impurity profiles to the maximum melt depth, a parameter which can be controlled very accurately by adjusting the energy fluence of the laser on the sample. By using multiple pulses dopant can be distributed evenly throughout the melted layer to form box-like profiles. These profiles, in conjunction with precise control of melt, enable exact vertical placement of the metallurgical junctions. The rapid thermal cycle, 1 billion times faster than a rapid thermal anneal (RTA), also allows emitter fabrication with no effect on the base-collector junction depth. The ability to place theses junction independently, in turn, allows simple fabrication of base regions less than 100 nm in width. Reproducibility of the process is ensured by *in-situ* diagnostics which enable real-time prediction of the junction depth [11]. Masking is achieved using conventional lithography with an aluminum thin film to reflect the laser energy from regions where doping is not desired.

N-P-N BIPOLAR FABRICATION

In this section the process used to fabricate narrow-base bipolar transistor is described. Key cross sections for the simple n-p-n transistor are shown in Fig.1 (a)-(c). The device, fabricated on <100> n-type 4-7 Ω.cm silicon, uses the substrate as the collector region. Since no buried layer is incorporated, low-resistivity substrate is required to reduce the collector resistance in the device. Initially, a 40 nm thermal oxide is grown followed by a 100 nm deposition of low-temperature undoped oxide (LTO). After the oxide deposition, 500 nm of pure aluminum is deposited. This layer serves as a reflectivity mask during the laser processing. Projection lithography is used to define the active base region. The Al is then wet etched and the resist removed. The pattern is transferred to the silicon by anisotropically etching the oxide in an O_2, CHF_3 plasma. In the next step, illustrated in Fig. 1(a), the active base region is formed using excimer laser assisted spin-on doping. The film containing boron dopant (B155 from Filmtronics) is used as dopant film for base formation. The dopant film was applied on the wafer surface. The emulsion surface was then baked at about 200°C while spinning at 2000 r.p.m in order to produce a uniform SOD thin film. Laser induced dopant incorporation was carried out in air, using a KrF excimer laser (LPX-105 Lambda Physik) providing large area (up to 6mm × 20mm) 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 laser energy used to irradiate the sample at this stage was set at 1 J/cm^2 per pulse, and 10 pulses were directed to the selected region to achieve the final junction depth of 220~250 nm.

After the base formation step, the Al (100 percent) mask is stripped and a 50 nm layer of LTO is deposited. This is followed by a second Al (100 percent) deposition. A masking sequence similar to that for the active base defines the emitter and collector contact. As shown in Fig.1 (b), these regions are laser-doped n$^+$ using a film containing phosphorous dopant (P509 from Filmtronics) as dopant film. The doping process is similar to that of base formation except that the laser energy was set at 0.75 J/cm^2 per pulse, and 10 pulses were directed to the selected region to achieve final junction depth of 70~150 nm.

After removal of the Al (100 percent) mask, an additional 250 nm LTO layer is deposited. Contact holes are defined and a 1-µm layer of Al-Si (1 percent) is sputtered and wet etched to form the base, emitter, and collector contact. A cross section of the completed device is shown in Fig.1(c).

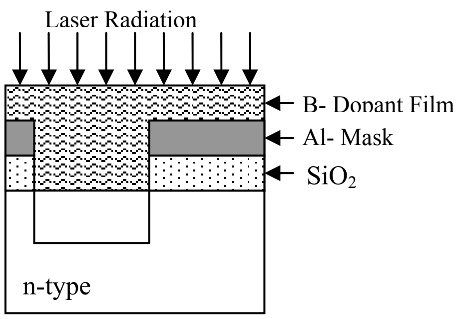

Fig.1 (a): Boron (B) laser-assisted doping step for active base formation

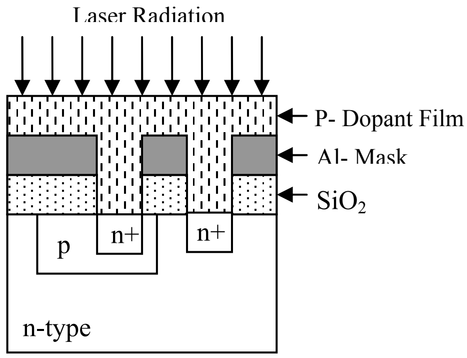

Fig.1 (b): Phosphorous (P) laser-assisted doping step for emitter region formation.

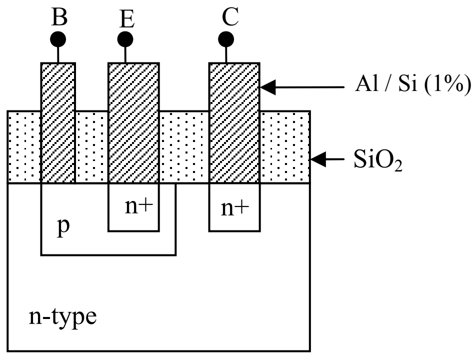

Fig.1 (c): Completed device cross section.

RESULTS AND DISCUSSION

Dopant Concentration Profile

Dopant impurity concentration and depth profiles were determined by SIMS, using a spectrometer (IMS CAMECA). Figs. 2 & 3 show data for material doped using different pulse energies and different numbers of pulses.

As in our earlier studies [12], changing the number of pulses does not change the depth of the molten region (formed largely during the first pulse), but affects the concentration of impurity atoms within it. When the first pulse melts the silicon substrate, dopant will be incorporated by a combination of mixing and diffusion. The higher solubility of dopants 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 3 to 10 pulses. During emitter formation only the energy of the driving pulse is varied. This allows fabrication of emitter regions which range in depth from 70~150 nm.

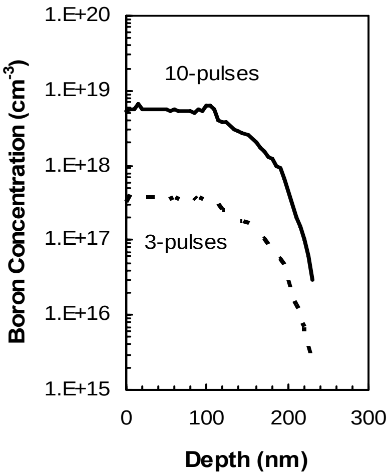

Fig.2: **SIMS** analysis results of boron profiles obtained using laser doping. Laser pulse energy used is 1 J/cm^2.

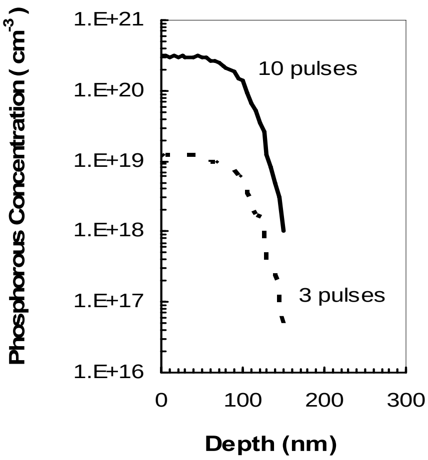

Fig.3: SIMS analysis results of phosphorous profiles obtained using laser doping. Laser pulse energy used is 0.75 J/cm^2.

Electrical Results

N-P-N transistor fabricated using excimer laser assisted spin-on doping exhibits promising electrical behavior. The dc characteristics are measured for the reverse leakage currents at the emitter-base and base-collector junctions, and forward-bias behavior of the collector and base currents (I_C and I_B). Both of these measurements give an indication of the quality of the excimer laser assisted spin-on doping junctions. Measurements of the base-collector reverse leakage current yield values less than 20nA at -5V. Emitter-base junction also exhibit low leakage currents, <1 nA at -5V and <1 pA at -1V. A plot of I_C and I_B versus base versus base-emitter voltage V_{be} for the device profiled in Fig.4 is given in Fig.5. The collector current is ideal over many decades of current, reaffirming the quality of the base-collector junction. The base current is less ideal. We attribute the nonideal behavior at low currents to leakage at the emitter-base junction. The ratio of the collector to base current gives the dc forward current gain, β_f. This parameter, which is important in digital design, is plotted in Fig.6. This figure demonstrates the maximum forward current gain in excess of 50 for the thin-base, laser doped device.

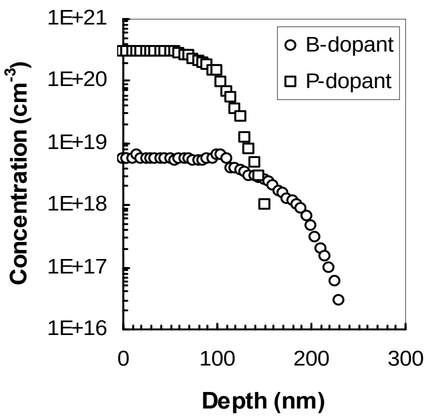

Fig.4: Emitter-base profile of a typical laser doped transistor. The base width of this device is approximately 100 nm.

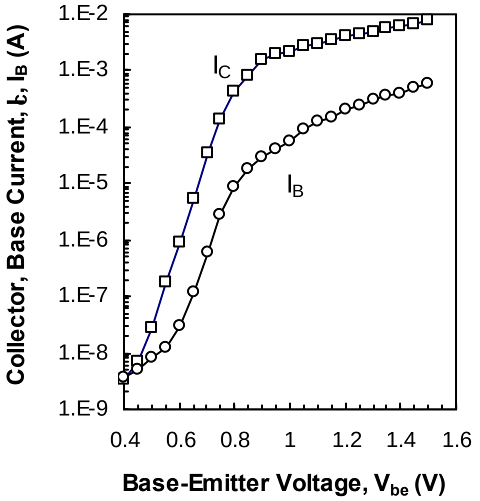

Fig.5: Gummel plot for n-p-n bipolar transistor fabricated using laser-assisted doping. The results in this figure are obtained from a transistor with the profile show in Fig. 4.

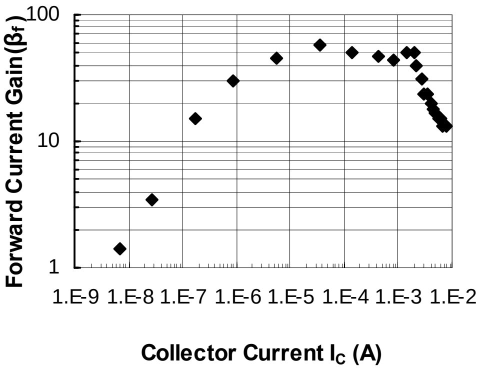

Fig.6. Plot of dc forward current gain versus collector current for the device shown in Fig. 5.
A maximum current gain of grater than 50 is exhibited.

CONCLUSION

In this paper we have presented the results of our efforts to fabricate to fabricate n-p-n bipolar transistor using excimer laser assisted spin-on doping, a pulsed UV laser-doping technology. We demonstrate that exceptional control of base and emitter profiles is possible using the new technique and show promising electrical results from transistor fabricated using the laser-doping method. The transistor exhibits current gain in excess of 50 with base widths less than 100 nm while the emitter-base and base-collector junctions exhibit very low reverse leakage currents.

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