Ultrashallow Defect-Free Junction Formation by Excimer Laser Annealing

Miloš Popadić*, Lis K. Nanver, and Johan van der Cingel

Abstract – **Reduced pressure CVD of arsenic has been investigated as a source of dopants in combination with excimer laser annealing (LA). Energy densities used for LA are above the Si melt limit and abrupt, highly doped, nearly defect-free, ultrashallow junctions have been formed. The junction depth is determined by the melt depth and is independent of the doping level, which is determined by the As deposition. Multiple LA of the surface deposited As layer was performed to yield improved uniformity while multiple cycles of As deposition plus LA have been performed to yield a higher dose and consequently lower sheet resistance, which in the case of three depositions drops to around 80 Ω/sq for layers with a doping depth of around 20 nm.**

Index terms – **Ultrashallow junctions, excimer laser annealing, RPCVD, Arsenic doping.**

I. Introduction

In silicon technology, ultrashallow doping profiles are of interest for both the formation of ultrashallow junctions and for increasing the surface doping of a contact region in order to lower the effective Schottky-Barrier Height or to secure a low-ohmic contact. The most common and at the same time the most demanding application is for the source/drain extensions of MOS devices [1]. Conventionally, low-energy ion implantation followed by rapid thermal annealing (RTA) is applied for introducing dopants at the surface, which has the advantage of accurate dose control but the disadvantage of introducing damage with associated transient enhanced diffusion, channelling and activation issues [2].

As a damage-free alternative, in a previous paper [3] we demonstrated that the surface deposited As monolayer can be used as a source for dopant diffusion into the Si if it is encapsulated under an oxide layer to prevent desorption. With annealing temperatures in the 700 ˚C – 850 ˚C range, ultra-shallow junctions with diffusion depths of less than 5 nm to at most about 15 nm can be fabricated and the corresponding I-V characteristics go from Schottky-like contacts to regular n-p junctions. However, with this process the dose and the diffusion depth are mutually dependent [4]. In addition, depending on the intended application, the thermal processing may exceed the allowed thermal budget.

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In this paper, we present a modified process in which the As dopants are deposited in a surface monolayer by CVD and driven in by melting the Si surface by high-power excimer laser annealing. Thereby we preserve the main advantage of a junction formation technology in which the implantation-related damage is avoided. Moreover, we also obtain a process in which the dopant dose is not directly influencing the junction depth. In the case of an amorphizing implantation, the interface largely determines the melt depth because the melt temperature of the α-Si is much lower than that of the c-Si. In the case of a deposited dopant, the melting of the underlying c-Si will determined the melt depth, which in turn is determined by the laser energy. The temperature budget remains limited only by the As deposition step, which in these experiments is performed at 700 ˚C, but can be reduced to 500 ˚C or possibly less. A similar combination of As deposition followed by laser annealing has been employed in the fabrication of n-MOSFETs, but the junction formation and the resulting characteristics have not been investigated in detail [5].

II. Experimental Procedures

Experiments were performed on p-type (100) 2-5 Ωcm Si substrates with a surface doping of $N_A = 10^{17}$ cm^{-3}. A 300 nm thick thermal oxide is grown in which windows were etched to the Si. An As deposition was then performed in the ASM Epsilon One reactor by reduced-pressure CVD. The deposition time was chosen to be so long that the formation of a complete monolayer was assured, but, if desired, it can be adjusted to yield only a fraction of a monolayer. The monolayer is then laser annealed in vacuum at room temperature with an Exitech XeCl excimer laser with a wavelength of 308 nm and pulse duration of 25 ns FWHM in the range of energy densities between 1100 mJ/cm^2 and 600 mJ/cm^2, which were varied across wafer columns. In a number of wafers, the As deposition and laser annealing steps were performed more than once. Finally, LPCVD TEOS oxide was deposited and contact windows to the As treated Si are formed by plasma etching of the TEOS almost to the Si surface of the windows and then wet landing on the Si by dip-etching in a 0.55% HF solution. This step is directly followed by metallization with sputtered Al/Si(1%) alloyed at 400 °C in forming gas. The back of the wafer was metallized and is the contact to the p-substrate. In that manner, van der Pauw and Kelvin test structures for sheet resistance and contact resistance measurements were fabricated, with an additional n-type contact implantation.

Two variations of the described process were made: first, the number of laser annealing pulses was increased in steps

from one to four while providing sufficient time between the pulses for cooling; and second, the number of cycles of As deposition plus LA was increased from one to three.

III. Results and Discussion

SIMS results

A direct measurement of the doping profile achieved by As deposition followed by LA is given by the SIMS measurements (Fig. 1). It can be observed that the melt depth and consequently the junction depth is between 10 nm and 20 nm, and that the doping in that region is above 10^{20} cm^{-3}, reaching $5{\cdot}10^{20}$ cm^{-3} close to the surface. Such combination of shallowness and high doping is comparable to the present state-of-the-art junctions formed by low-energy implantation followed by RTA, but is expected to create significantly fewer defects.

It can be also observed that the total dose is smaller than the full monolayer (ML) surface concentration of $N_{surf} = 6.8{\cdot}10^{14}$ cm^{-2}, and that it shows a dependency on the LA energy density. Although it is known that the As surface coverage is unstable in air at room temperature, this effect is not fully understood and needs to be further investigated. The profile in the melted region is not flat but slowly increasing towards the wafer surface, which can be explained by a finite diffusion coefficient of As in the melted phase. A theoretically alternative explanation is As segregation during recrystallization, but no evidence of it was found in implanted and laser-annealed samples.

Doping profiles of samples that have undergone three cycles of As deposition and LA are also presented in Fig. 1. However, the SIMS measurement on them was performed at a much higher speed and consequently lower accuracy. This means that the profiles of these samples are not well comparable to the profiles of samples with only one As deposition and LA. Yet, it is clear that with three cycles deeper junctions are formed. This is mostly due to thermal diffusion during the subsequent As depositions. This temperature, however, can be reduced significantly below 700 ˚C that was used here. In addition, it can be observed that the increase in the total dose is far below 300 % that would be expected. It is plausible that LA adversely affects the Si surface and inhibits the subsequent As deposition.

Sheet resistance measurement results

Sheet resistances of all samples are presented in Fig. 2. If we consider the case of a single As deposition with a single LA pulse, first it can be observed that little variation as a function of LA energy density exists beyond $E = 900$ mJ/cm^2, which is close to the Si melt limit in case of crystalline Si [6]. A certain decrease in sheet resistance as a function of LA energy density does exist, and that can be attributed to the increase in junction depth which leads to the decrease in As concentration and increase in electron mobility. Measured sheet resistance values correspond well with the SIMS obtained doses and expected mobility [7]. The sheet resistance of the non-annealed devices is not the sheet resistance of the background p-type Si since the contact pads were n-type implanted; instead, it monitors the very small pad junction leakage current.

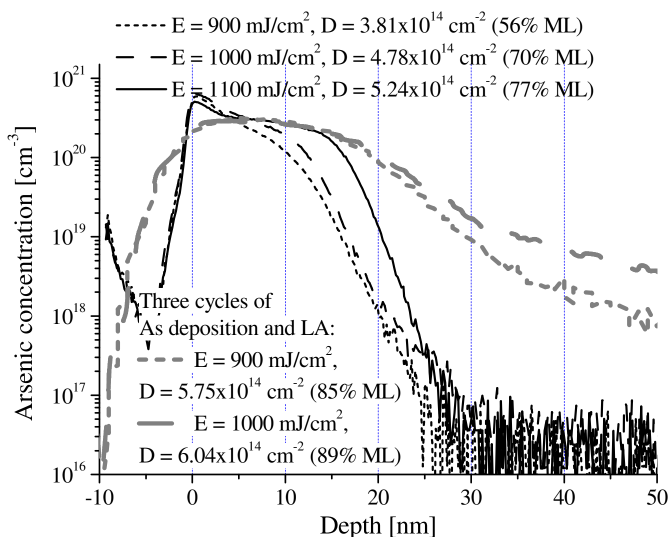

Fig. 1. SIMS results for samples with a single As monolayer deposition followed by LA and three cycles of As deposition plus LA for different laser energy densities (*E*). The total doses (*D*) are given, also as a function of a monolayer concentration (*ML = Nsurf*).

Significant spread over the wafer in the measured values of sheet resistance can be observed, and the spread increases as the LA energy density decreases. Such a spread implies a certain non-uniformity, which can, besides the variations observed from measurement point to measurement point, also mean that non-uniformities within the individual van der Pauw structures will introduce a measurement error. Nevertheless, from Fig. 2 it can be observed that increasing the number of LA pulses greatly reduces the non-uniformity and the sheet resistance drops to its optimal, minimal value. The evidence for the cause of this spread is not conclusive, e.g. a possible non-uniformity in the As surface coverage or drive-in is expected to diminish with multiple pulses due to lateral diffusion, but it is most likely that the spread is related to non-uniform Si melting, which will be discussed further below.

Multiple cycles of As deposition plus LA consistently reduce the sheet resistance as the As dose increases. Thereby, in only three cycles, sheet resistances well below 100 Ω/sq are obtained. In addition, sheet resistances below 1000 Ω/sq have been measured in devices annealed at only 800 mJ/cm^2. Considering the extremely short laser pulse duration with the short cooling time, it is a well-established fact that the As cannot have thermally diffused into the crystalline Si. Instead, we can conclude that even the energy density of 800 mJ/cm^2 can lead to melting of the As covered Si surface.

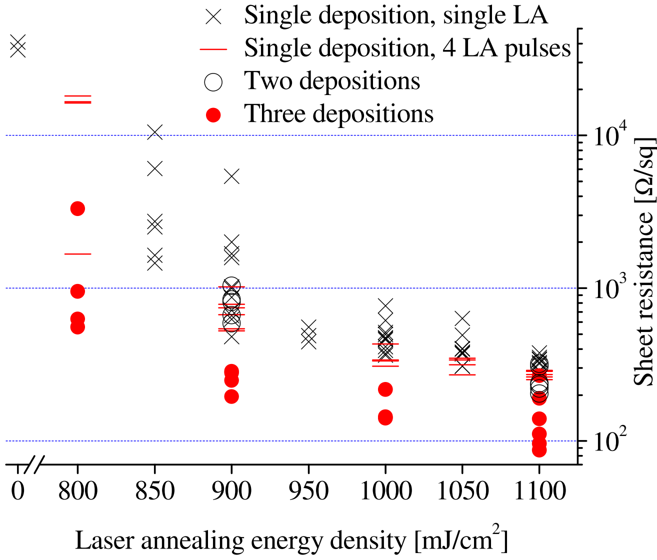

Fig. 2. Measured sheet resistance values for different laser-annealed As monolayers, obtained from van der Pauw structures.

Contact resistance measurement results

Specific contact resistances determined from measurements on a set of Kelvin test structures with different contact areas are presented in Fig. 3. Since the sheet resistance of the laser annealed regions forming the diffusion taps of the Kelvin structures is higher than about 100 Ω/sq, the necessary geometric correction of the measured value is also high. This correction can be evaluated by [8]:

$$\Delta R_c = \frac{4\rho_s \delta^2}{3}\left(1+\frac{\delta}{2(W-\delta)}\right), \qquad (1)$$

where ρ_S is the sheet resistance of the layer, and δ is the difference in size between the diffusion pad width W and the contact window width. The estimated corrections are also given in Fig. 3.

It can be observed that in the case of a single deposition pulse the measured values are only slightly higher than the estimated correction. The correction estimate includes several factors that limit its accuracy: first, a significant spread in the sheet resistance was measured (Fig. 2), second, the geometry factors are process dependent and not exactly known, and third, the formula (1) used for the calculation of the correction involves mathematical approximations. Therefore, since practically all measured values are in the same range as the correction it is reasonable only to speak of them as the upper limit of the contact resistance, which is most likely much higher than the real specific contact resistance.

The inaccuracy of the estimated corrections is particularly evident in the case of devices with two or three As depositions. In these devices, the estimated correction is larger than the apparent, measured contact resistance which would mathematically indicate a negative true contact resistance, which is physically impossible. Therefore, it can only be concluded that the real specific contact resistance is in the range from zero to somewhere below the measured value (depending on the estimated minimal correction), which is symbolically indicated in Fig. 3 by the drop lines of the measured points. For contacts with the same level of expected doping, the true contact resistance is commonly around one order of magnitude lower than the values measured here [9].

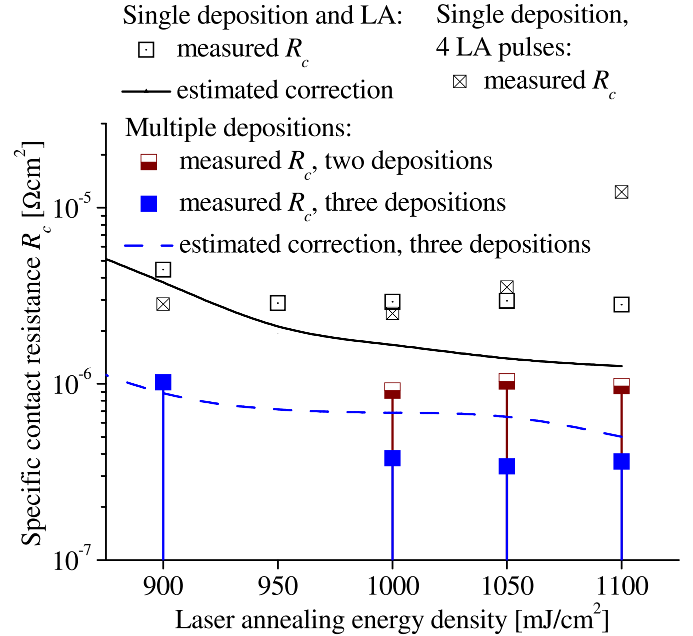

Fig. 3. Specific contact resistances of samples prepared in a different manner. Squares mark the measured values, while lines show the estimated correction due to current. In cases where the estimated correction is larger than the measured value this is indicated by a drop line.

Devices processed with four laser annealing pulses yield essentially the same contact resistances as the devices with a single LA pulse, with the notable exception of the very high resistivity observed for an energy density of 1100 mJ/cm². This result indicates that such high energy density is detrimental to the Al to Si contact properties, and the energy agrees well with the onset of laser-induced period surface structures [10].

IV. Conclusions

Arsenic deposition on the Si wafer surface followed by excimer laser annealing at energies above the melt limit has been successfully used in the fabrication of ultra-shallow junctions. This process enables the fabrication of nearly defect-free, extremely abrupt junctions with a very limited thermal budget. Significant spread, arguably due to non-uniformity of the melt depth has been observed since this method does not profit from an amorphization of the Si surface as is the case for dopant implantation. However, this problem is shown to be largely alleviated by LA with multiple, thermally separated pulses. The doping and the junction depth can be independently controlled and varied over a very flexible range. At the same time very low sheet resistances

well below 300 Ω/sq and very shallow junctions of around 15 nm are obtained, which makes this technique an interesting candidate for the fabrication of source/drain extensions for future MOSFETs.

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