Modeling electrical characteristics of laser tuned silicon microdevices

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ABSTRACT

Highly accurate resistances can be made by iteratively laser inducing local diffusion of dopants from the drain and source of a gateless field effect transistor into its channel, thereby forming an electrical link between two adjacent p-n junction diodes. These laser tuned microdevices have been electrically characterized and their current-voltage (I-V) behaviors are linear at low voltages and sublinear at higher voltages where carrier mobility is affected by the presence of high fields. Considering that the microdevice is a one dimensional trap less n+ υ n+ structure, we have developed a theoretical current-voltage equation that satisfies these experimental results.

Keywords: Laser trimming, laser tuned microdevices, laser induced diffusible resistance, microelectronics, highly accurate resistance.

INTRODUCTION

Due to the inevitable fabrication process variabilities, analogue microelectronics circuits' functionalities are frequently altered and trimming techniques have to be used to accurately adjust some microdevices' characteristics. We have recently proposed a new technique to finely tune analogue microelectronics' circuits that presents the advantages of being very accurate, using very small die area, and being easily integrated into any actual CMOS processes without additional fabrication steps [1-5]. A patent disclosing the detailed device structure and creation method has been recently accepted [3]. In this paper, after reviewing the principle of the technique, we present the electronic characterization and modeling of these new microdevices. We show that they present an excellent linear current-voltage behavior at usual microelectronics' voltages and that at higher voltages, the sublinear behavior is due to a saturation of the majority carriers' velocity.

PRINCIPLE OF THE LASER TRIMMING METHOD

The laser trimming technique shown schematically in Figure 1 is performed on a device structure consisting of a gateless MOSFET fabricated by a conventional CMOS process [1,2]. For a n-type resistor, the device structure consists of two highly doped regions formed by implantation inside a p-well, resulting in two p-n junctions facing each other. Before the laser trimming operation, the only current that can flow through the device is the p-n junctions leakage current, resulting essentially in an open circuit. Focusing a laser beam on the gap region between the two junctions causes melting of the silicon, resulting in dopant diffusion from the highly doped regions to the lightly-doped gap region. Upon removal of the laser light, the silicon solidifies, leaving the diffused dopants in a new spatial distribution forming an electrical link between the highly doped regions. This laser-diffused link constitutes the tuned microdevice. Tight control of process parameters is necessary to create efficiently these laser tuned microdevices while avoiding damage to adjacent devices and structures. These parameters are the laser spot size, the pulse duration, the laser power, the number of laser expositions and the position of the laser spot relatively to the device. By varying the parameters between each laser intervention, one can accurately control the tuning of the device. Scanning electron microscopy and transmission electron microscopy show that the laser process has no effect on the dielectric multilayers nor on the dielectric/silicon interface[2,6].

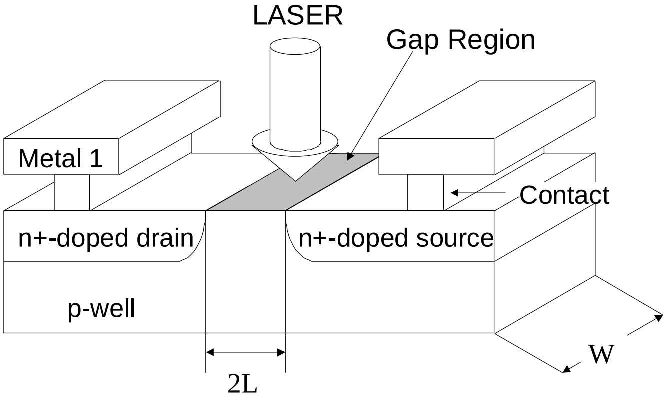

Figure 1 Schematics of the laser tuned microdevices technique

ELECTRICAL CHARACTERIZATION

Current-voltage (I-V) characteristics have been measured using a Hewlett Packard 4155A semiconductor parameter analyzer with a four-wire test procedure on samples placed in a Faraday cage at room temperature. The I-V curves of typical laser tuned resistances are presented in Figure 2. Devices with few kΩs in resistance present an excellent linearity over the range of voltages normally used in microelectronics (±1.5V). In Figure 3, I-V characteristics of tuned resistances with nominal gap between 0.6 µm and 1.4 µm are plotted up to 7.5 volts, the maximum applicable voltage on our test chip before breakdown. They showed a non-linear behavior primarily related to the carrier velocity saturation at moderate fields. The lines on this figure correspond to the model presented in the next section.

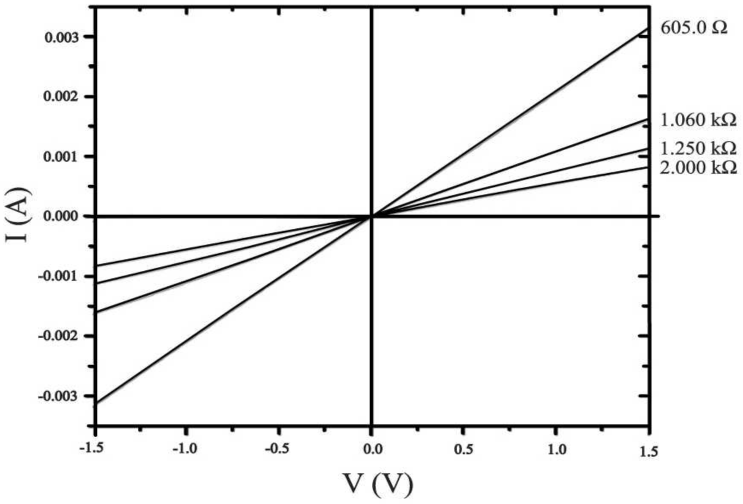

Figure 2: Current-voltage characteristics of four laser diffusible resistances at low voltages (< 1.5V) usually used in microelectronics.

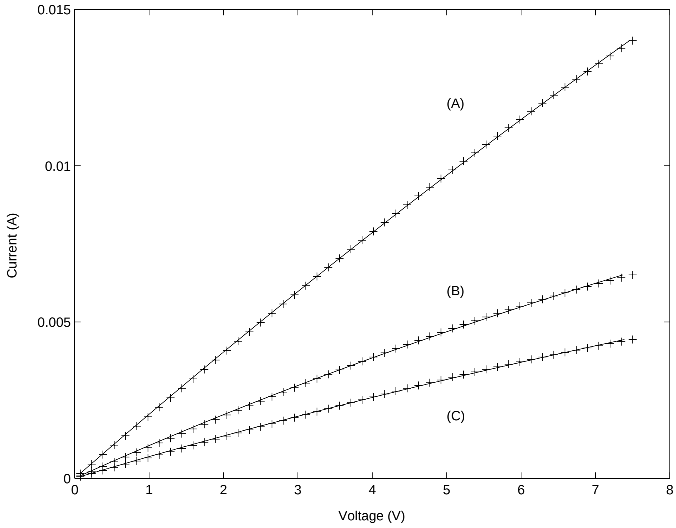

Fig. 3 Current-voltage (I-V) plot of the experimental data (crosses) and fitted model (line) for three typical laser-tuned resistors of parameters, 500, 1000, 1500 Ω. The lines are calculated from the model introduced below with the following characteristics: (A) R = 500Ω, N_D = 1.45x10^{18}cm^{-3}, L = 0.6µm ; (B) R = 1kΩ, N_D = 5.02x10^{18}cm^{-3}, L = 1.0µm; (C) R = 1.5kΩ, N_D = 2.66x10^{18}cm^{-3}, L = 0.6µm.

MODELING THE LASER TUNED MICRODEVICES

The laser has the effect of diffusing dopants from the source and drain into the channel as shown schematically on the top part of figure 4. After diffusion, the microdevice presents a n+ υ n+ (or p+ π p+ depending on the highly doped region type) structure with non-abrupt junctions. As it is quite often done in a first analysis of a microdevice, one can approximate this device by a one dimensional structure with two abrupt junctions, as shown in Figure 4.

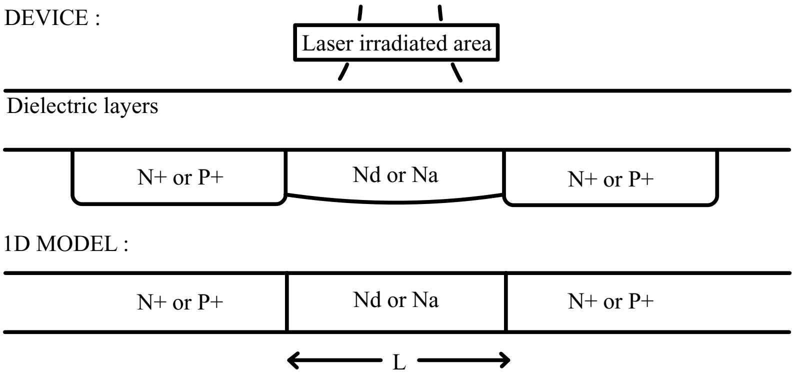

Fig. 4 Schematics of the one dimensional model applied to the geometry of a laser-diffused resistor.

The J-V relation of a n+ υ n+ structure has been extensively studied in the past [7-12]. Single carrier transport can be described by the drift-diffusion equation where the diffusion current is ignored and by a field dependent mobility expression based on the Canali et al. model [13]. An impurities' concentration dependent low field mobility model was also used [14]. Mobility degradation is implicitly assumed since important electric fields as high as 10^{5}V/cm are applied on the laser-tuned resistors. Therefore, the current density is given by:

$$J = nq\frac{\mu_0 E}{1+\left|E/E_C\right|} \tag{1}$$

where q is the elementary electrical charge, E_C is the electric field necessary to observe mobility degradation and μ_0 the low field mobility. At low applied electric field E, we observe an ideal ohmic relation. The charge-trap density is considered small enough to be ignored and current continuity yields to $dJ/dx = 0$. By combining equation (1) with Poisson's equation, where all the impurities N_D are ionized (leading to $n = N_D$ at room temperature), we obtain the differential equation:

$$J = q\left(N_D - \frac{\varepsilon}{q}\frac{d}{dx}E\right)\frac{\mu_0 E}{1+\left|E/E_C\right|}. \tag{2}$$

where ε is permittivity of the semiconductor. We then make the "virtual cathode approximation" which stipulates that the electric field is equal to *0* at $x = 0$ and a transcendent solution is obtained by integration of the differential equation (2):

$$-\hat{j}\hat{x}\left(\frac{1}{\hat{j}}-1\right)^2 = \left(\frac{1}{\hat{j}}-1\right)\hat{e} + \ln\left(1-\left(\frac{1}{\hat{j}}-1\right)\hat{e}\right) \tag{3}$$

with the dimensionless variables :

$$\hat{j} \equiv \frac{J}{qN_D\mu_0 E_C}, \tag{4a}$$

$$\hat{e} \equiv E/E_C\,, \tag{4b}$$

$$\hat{x} \equiv \frac{-xN_D q}{\varepsilon \cdot E_C}. \tag{4c}$$

A solution J(V) is very hard to obtain because we do not have a direct relation between J and E. In previous studies, this solution was investigated only in certain asymptotic conditions because of its nature and complexity of its numerical resolution. Unfortunately, most of the current-voltage (J-V) plot of a typical laser-diffused resistor is within the transition between pure ohmic conduction and the effect of mobility degradation and space-charge-limited current. This transition cannot be only evaluated in asymptotic conditions.

It is reasonable to consider that for a positive applied voltage V we will get negative values of J, E and E_C. Since

$$-\hat{j}\hat{x}\left(\frac{1}{\hat{j}}-1\right)^2 \le 0, \quad \forall\hat{x} \;\; and \;\; \forall\hat{j}\,, \tag{5}$$

the logarithmic term will always dominate on the right hand side of equation (4) in our case. We can then approximate our transcendent solution by

$$-\hat{j}\hat{x}\left(\frac{1}{\hat{j}}-1\right)^2 \approx \ln\left(1-\left(\frac{1}{\hat{j}}-1\right)\hat{e}\right). \tag{6}$$

It is now possible to express the electric field $E = dV/dx$ as a function of the current density, yielding after integration over the device's length L to the V-J relation:

$$V = \frac{E_C^2\varepsilon}{N_D q}\frac{-\hat{j}^2}{\left(\hat{j}-1\right)^3}\left\{\exp\left(\frac{-\hat{x}_L}{\hat{j}}\left(\hat{j}-1\right)^2-1\right)+\frac{\hat{x}_L}{\hat{j}}\left(\hat{j}-1\right)^2-1\right\} \tag{7}$$

where

$$\hat{x}_L \equiv \frac{-LN_D q}{\varepsilon E_C}. \tag{8}$$

This equation was applied to fit the experimental curves of Figure 3 with only N_D and E_C as free parameters. The three fitted curves give values of N_D between 10^{18}cm^{-3} and 5x 10^{18}cm^{-3} which correspond to the expected doping level in the melted region after the laser induced dopant diffusion from the highly doped regions of $5x10^{19}$ cm^{-3}. The excellent fit suggests that equation (7) described very well the electrical behavior of the laser tuned microdevices.

CONCLUSIONS

Highly accurate resistors compatible with CMOS technology can be easily made by laser inducing dopant diffusion. These new microdevices have very linear I-V curves at the usual microelectronics operating voltages and present non-linear behavior due to carrier velocity saturation. Experimental results are well described by a simplified analytical solution of the one dimensional trap-less n+ υ n+ or p+ π p+ diodes' model.

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