LASER INDUCED LOCAL MODIFICATION OF SILICON MICRODEVICES: A NEW TECHNIQUE FOR TUNING ANALOGUE MICROELECTRONICS

Michel Meunier [a,b], Mathieu Ducharme [a], Jean-Yves Degorce[a], Yougui Liao[a] and Alain Lacourse [b]

[a] École Polytechnique de Montréal, Laser Processing Laboratory, Case Postale 6079, Succursale. Centre-ville, Montréal (Québec), Canada, H3C 3A7
[b] LTRIM-Technologies, 440 Blvd Armand Frappier, suite 140, Laval, Québec, Canada, H7V 4B4

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 the channel, thereby forming an electrical link between two adjacent p-n junction diodes. Using transmission electron microscopy, we showed that the laser induced diffusible resistance can be performed without any structural modification to the microdevices. Current-voltage (I-V) characteristics of these new microdevices are shown to be linear at low voltages and sublinear at higher voltages where carrier mobility is affected by the presence of high fields. A process model involving an approximate calculation of the laser melted region in which the dopant diffusion occurs has been developed. Experimental results are well described by the proposed model.

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

INTRODUCTION

Due to the inevitable fabrication process variabilities, analogue microelectronics circuit functionality are very often 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 which presents the advantages of being very accurate, using very small die area, and being easily integrated into any actual CMOS process without additional steps [1,2]. 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 the modeling of these new microdevices and show that they present excellent current-voltage linear behavior at usual microelectronics voltages. Furthermore, process modeling based on the laser induced silicon melted region calculation is introduced and successfully compared to experimental results.

PRINCIPLE OF THE LASER TRIMMING METHOD

The laser trimming technique shown schematically in figure 1 is performed on a device structure consisting of a MOSFET, without the gate, fabricated by a conventional CMOS process[1,2]. For an n-type resistor, the device structure consist of two highly doped regions formed by implantation into a p-well, resulting into two p-n junctions facing each other. Before performing laser trimming, 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 special distribution forming an electrical link between the highly doped regions. This laser-diffused link constitutes the trimmed resistor. Tight control of process parameters is necessary to create efficiently these laser diffusible links 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 relative to the device. By varying the parameters between each laser intervention, one can accurately control the tuning of the device.

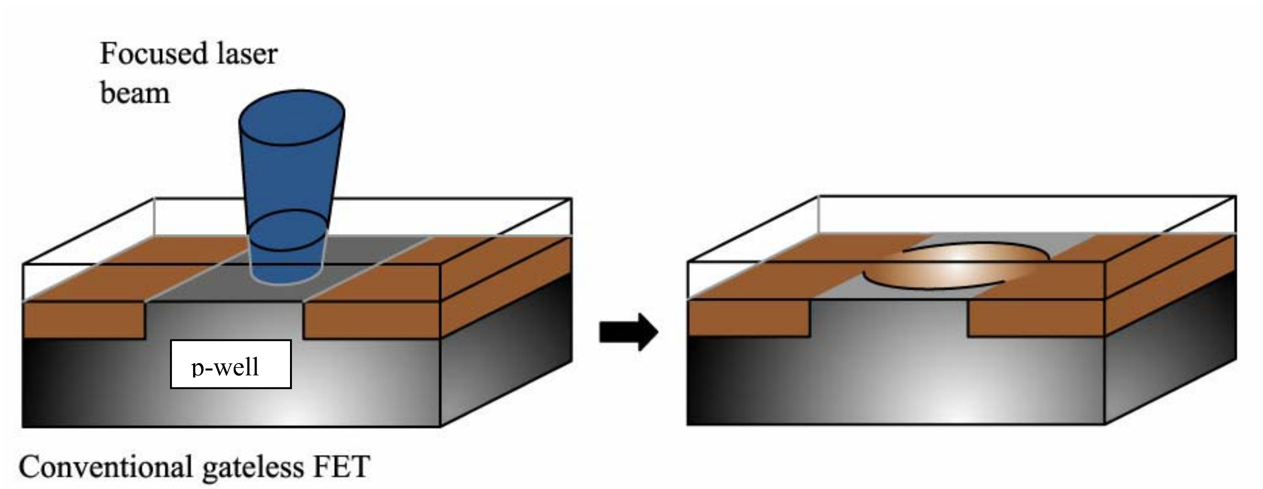


Figure 1: Schematics of the laser induced diffusible resistance.

STRUCTURAL CHARACTERIZATION

We have performed transmission electron microscopy (TEM) on untrimmed and trimmed samples using a Philips CM30 system operating at an acceleration voltage of 300 kV. The ultra-thin TEM samples with a uniform thickness were prepared by an HITACHI FB-2000A focused ion beam (FIB) instrument. Figure 2 shows the cross-section of a gateless field effect transistor with a nominal source to drain distance of 0.6μm. The rounded shape of the oxide layer is due to a field oxide that is grown in the absence of the gate between the highly doped regions. We note that there is no effect due to the process on the dielectric multilayers or on the dielectric/silicon interface. In addition, as expected and seen on the trimmed microdevice, dopant concentrations in the source and drain regions close to the gap has been lowered due to the diffusion into the gap.

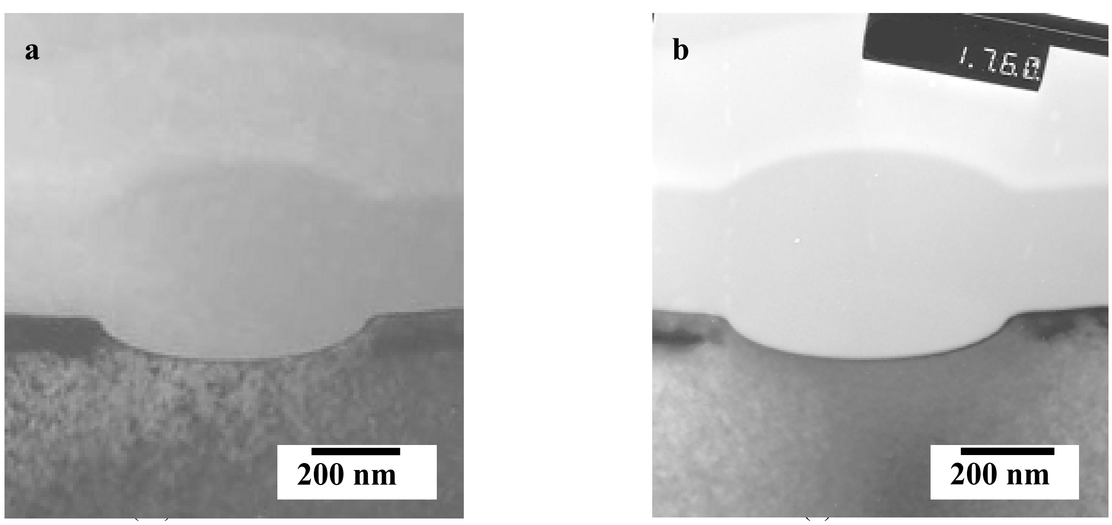
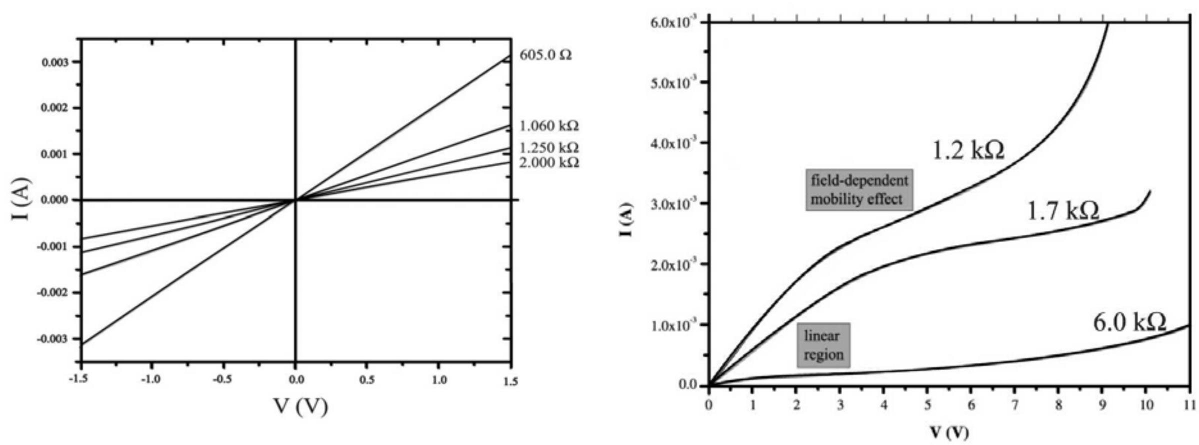


Figure 2: Bright field TEM images of an untrimmed (a) and trimmed (b) microdevice.

ELECTRICAL CHARACTERIZATION

Current-voltage (I-V) characteristics have been measured using a Hewlett Packard 4155A semiconductor parameter analyzer. The current-voltage curves of typical laser diffusible resistances are presented in Figure 3. Lower resistance devices (lower than few kΩ) present an excellent linearity over the range of voltages normally used in microelectronics (±1.5V), while higher resistance devices show non-linear effects and a relatively small (-0.3V to 0.3V) linear region. In Figure 3(b), I-V characteristics are plotted up to relatively large applied voltages. They show a non-linear behavior primarily related to the carrier velocity saturation at moderate fields and to an avalanche effect at high fields, reducing the resistance which permits a greater current to flow into the device.



(a) (b)

Figure 3: Current-voltage characteristics of three laser diffusible resistances at (a) low voltages (< 1.5V) and (b) at high voltages.

PROCESS MODELING

Modeling this process involves a time-dependent three-dimensional (3D) calculation of the temperature due to the laser irradiation [4], followed by a dopant distribution calculation using Fick's law. Device characteristics can then be evaluated by solving the three differential coupled equations to obtain the 3D distributions of electron and hole concentrations, as well as the electric field in the device presenting a non-uniform dopant distribution. Some insight on process modeling can be obtained by using careful approximations. We consider the effect of a focused laser beam incident on a n+-p-n+ silicon structure, resulting in the diffusion of dopants into silicon. Because the diffusion coefficient of dopants in liquid Si (for Arsenic, D=3.3x10^{-4}cm^2/s and 6.8x10^{-3}cm^2/s corresponding respectively to the fusion temperature (T=1683K) and to a reasonable temperature of molten Si (T=3000K) [5]) is almost seven orders of magnitude higher than that of crystalline Si, we assume that only dopants in the silicon melt diffuse. During the laser pulse, the silicon melt dimension increases and then decreases as the pulse ends. Therefore, we propose that only the maximum melted region (as denoted by r_{melt} on the Si surface) has to be determined in the temperature calculation; the dopants located outside this region are assumed to be immobile.

To calculate the maximum melted region one has to solve in principle the basic energy balance equation including the laser source term as well as the conduction, convection and radiation heat losses. Since the radiation term is essentially negligible compared to the conduction term and since, in a first approximation, we can neglect convection because the pulse melting time is lower than few µs. Further approximation on the pulse heating source can be made by comparing the heat diffusion length $l = \sqrt{Dt_p}$ to the light absorption length α^{-1} and the beam radius r_0. For pulse width in the range $0.03\mu s \le t_p \le 10\mu s$ considered here, l lies between 1 and 20 μm. For a focused spot of 1 μm, and for a typical band-to-band absorptivity of $10^{-5}cm^{-1}$, we can therefore approximate the laser irradiation as a quasi point source. Assuming furthermore, that the materials properties are isotropic, the melt region can be described by a hemisphere, of radius $r(t)$. In the framework of the Stefan problem [6], the energy density balance is evaluated at the moving liquid-solid interface:

$$j_{in}dt = j_{out}dt + Ldr \quad , \tag{1}$$

where L is the latent heat, $j_{in} = \kappa_l \left(\frac{\partial T}{\partial r}\right)_{r_m}$ in the liquid phase, $j_{out} = \kappa_S \left(\frac{\partial T}{\partial r}\right)_{r_m}$ in the solid phase where κ_l and κ_s are the thermal conductivities of the liquid and solid, respectively. In the presence of strong convective flow as usually seen in laser-irradiated materials [7], we will assume that the total energy absorbed at the liquid surface is transported to the liquid-solid interface. Furthermore, we neglect the energy lost by the heated surface, as it can be estimated to represent less than 1% of the input energy. Consequently, the energy balance at the outer surface of the molten pool may be written as:

$$dE_{in} = j_{out}Sdt + LSdr \tag{2}$$

where $S = 2\pi r^2$ is the surface of the hemisphere. On the left-hand side of Eqn.(2), $dE_{in} = P(1-R_l)dt$ is the energy released by the laser during dt in a liquid semiconductor of reflectivity R_l. On right-hand side of Eqn. (2), j_{out} is approximated by the linearization to $j_{out} = -\kappa_S \nabla T \approx -\frac{\kappa_S \Delta_m T}{\xi\sqrt{Dt}}$, where $\Delta T_m = T_m - T_\infty$ and T_∞ is the substrate temperature, D is the thermal diffusivity in the solid at the fusion temperature T_m and ξ is a constant usually fixed at 1. With these approximations, Eqn. (2) becomes:

$$P(1-R_l)dt = L2\pi r^2 dr + \frac{\kappa_S \Delta_m T}{\xi\sqrt{Dt}} 2\pi r^2 dt \quad . \tag{3}$$

Using the following dimensionless quantities

$$x = \frac{2\pi}{(1-R_l)r_0} r \quad ; \quad \tau = \frac{4\pi^2 D}{(1-R_l)^2 r_0^2} t \quad ; \quad p = \frac{P}{DLr_0}$$

Eqn. (3) can be rewritten in the equivalent form

$$x^2 \frac{dx}{d\tau} + Ax^2 \tau^{-1/2} = p \tag{4}$$

where we have introduced a dimensionless material-properties-only constant

$$A = \frac{\kappa_s \Delta_m T}{\xi DL} \tag{5}$$

whose value is close to 1 for most semiconductors. Unfortunately, it seems that the ordinary differential equation (ODE) (4) does not have an exact analytical solution. A comprehensive study of Eqn.(4) can be found in reference [8]. An analysis of the asymptotic behavior of $x(\tau)$ for $\tau \to \infty$ allowed to obtain the following approximate analytical solution, using the initial value $x(0) \approx 0$:

$$x(\tau, p) \approx \frac{2A^{1/4} p^{1/4} \tau^{3/8}}{\sqrt{1 + 4A^{3/2} p^{-1/2} \tau^{1/4}}} \tag{6}$$

When compared with numerical solutions, it was found that the error of the approximation (6) is smaller than 3 % for $t \geq 0.03 \mu s$.

A way to compare experimental results and the proposed model is to determine the conditions which give a fixed melted radius. This can be done in the following manner. Before laser irradiation, the resistance of the microdevice has essentially an infinite value. According to the proposed model, process parameters must be such that the melted region must reach the source and the drain before the dopants begin to diffuse into the channel. For a determined laser power, a minimum pulse width is required to diffuse sufficient dopants to produce a resistance. We have performed measurements on microdevices with a 1.7 µm source to drain distance and for source and drain initial concentrations of 5 X 10^{19} cm^{-3}. Figure 4 shows experimental results to produce a resistance of a finite value (readable on the multimeter, i.e. between 10^7 and 10^8 Ω) with only *one* laser irradiation. Note that to obtain 10^8 Ω on the multimeter, a silicon resistivity of 10^3 Ωcm is needed corresponding to a dopant concentration as low as 10^{13} cm^{-3} in the channel on the average [9]. For fixed values of τ and x, the corresponding power p can be obtained by solving Eqn.(6) for p. The solution, which is the positive real root of a second order polynomial, is

$$p = \frac{x^2}{32 A \tau^{3/2}} \left(32 A^2 \tau + x \left(x + \sqrt{x^2 + 64 A^2 \tau} \right) \right) \tag{7}$$

The agreement between the results and our calculation using Eqn.(7) with $r_{melt} = 0.85 \mu m$, is very good. Divergences at laser powers smaller than 0.5 W are probably due to the fact that the assumption of neglecting the temperature gradient term in the liquid in Eqn.(3) is no longer valid.

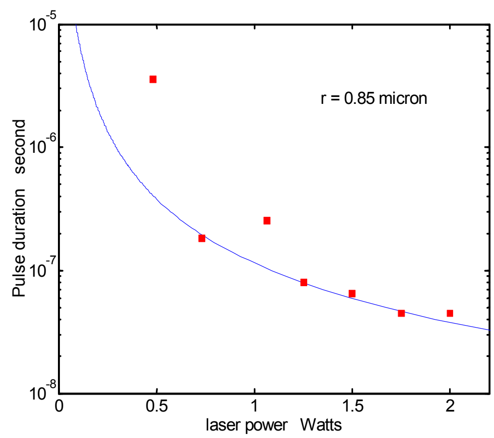


Fig. 4: Minimum time needed to create a resistance of finite value (i.e. between 10^7 and 10^8 Ω) as a function of laser power for one laser irradiation. Small squares are experimental results and the line is calculated from the model.

CONCLUSIONS

Highly accurate resistances 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 followed by avalanche effects. We clearly showed that the process is based on the dopant diffusion into the melted silicon and our calculations are in good agreements with experimental results. The authors are grateful to Jean-Paul Lévesque and Hugo St-Jean for technical assistance and Yvon Savaria for stimulating discussions. The authors wish to thank Digital Instruments and FEI Company for AFM-SCM and FIB measurements respectively.

REFERENCES

[1] M. Meunier, Y. Gagnon, Y. Savaria, A. Lacourse and M. Cadotte, Proc. of SPIE, 4274, 385-392 (2001)
[2] M. Meunier, Y. Gagnon, Y. Savaria, A. Lacourse and M. Cadotte, Applied. Surface Science, 186, 52-56 (2002)
[3] Y. Gagnon, M. Meunier, Y. Savaria, , US Patents 09/332,059 and PCT # 06042-002-WO-1 by LTRIM Technologies Inc. (2001)
[4] D. Bäuerle, Laser Processing and Chemistry, 3rd ed., Springer, Berlin (2000)
[5] H. Kodera, J. Appl. Phys., 2 **212** (1963)
[6] H.S. Carslaw and J.C. Jaeger, Conduction of Heat in Solid, Clarendon Press, Oxford (1988)
[7] A.C. Tam, J.K. Pour and C.P. Grigoropoulos, IEEE Transactions on Magnetics, 32, 3771, (1996)
[8] A. Saucier, J-Y. Degorce and M. Meunier, submitted to SIAM Journal on Applied Mathematics.
[9] see for example, Robert F. Pierret, “Advanced Semiconductor Fundementals”, Modular Series on Solid State Devices, volume VI (1989)