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Modified Pearson Model for High-Energy Multi-Charge Implantation and Impurity Activation for Sensor Microsystems

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***Abstract*—The mathematical Gauss and Pearson models, that qualitatively determine the physical processes of ion doping of acceptor (p) and donor (n) impurities, are used for the simulation of silicon submicron large scale integrated (LSI) structures. Such models are the basis of CAD-technology for calculating the concentration profiles of diode and transistor structures. This paper presents a modified Pearson model, which with high accuracy simulates the process of dual multi-charge implantation of boron (B^+, B^{++}) and phosphorus (P^+, P^{++}) ions at the process of the formation of the isotype p^+-p and n^+-n contacts, which at present form the basis of combined drain-source areas of the CMOS submicron high speed structures.**

Keywords—Pearson model, multi-charge implantation, sensitive element, MOS transistor, Czochralski process, sensor microsystem

I. Introduction

Today, ion implantation is used at any stage of alloying in submicron technology of large-scale integrated circuits (LSICs). Ion implantation applications are distinguished by their dose and alloying energy. This area can be expanded using multi-charge dual ion implantation, where charge multiplicity (two or more) plays the main role. This technological technique allows to increase significantly the performance of almost all types of transistors (including LSIC-transistors) and to reach the level of 150-180 GHz. In particular, this method is effective for the formation of both isotype homo- and hetero n^+-n and p^+-p junctions used in submicron LSIC-technology, first of all for epitaxial gallium arsenide on Si-substrates [1-3].

For the simulation of silicon submicron structures of LSICs, mathematical Gaussian [1] and Pearson models [2] were used that accurately determine the physical processes of ion doping of acceptor and donor impurities. These models are the basis of technology for calculating the concentration profiles of transistor and diode structures [3-5].

This article presents a modified Pearson model, which simulates with high accuracy the process of dual implantation of boron (B^+, B^{++}) and phosphorus (P^+, P^{++}) ions at the formation of isotype p^+-p and n^+-n contacts used as a base of source-drain areas of CMOS submicron structures of high performance [6-8].

High-temperature diffusion processes are replaced by processes of ion doping (ID) and individual treatment of the plates, at increasing the degree of integration of the LSI-structures [9,10] and reducing the minimum size of elements at the transition to Si-plates of large diameter (more than 150 mm).

The use of high-energy multi-charge ions allows all diffusion profiles to be replaced with implanted ones, including the protective regions of local oxide and pockets in CMOS structures. Therefore, ion implantation is becoming the main method of doping in submicron technology for the formation of LSI structures. This is due to the following factors [5]:

- ion implantation provides high precision and reproducibility of profiles at different depths;

- ID process is attributed to high purity electron-ion processes;

- implantation as a low-temperature process is not energy-intensive, and the activation of impurities is provided by photonic or laser annealing;

- ID covers a very wide range of concentration profiles from 10^{13} to 10^{20} cm^{-3}, which is practically impossible to implement by diffusion.

II. Comparative Parameters of Gauss and Pearson Distributions

Mathematical Gauss and Pearson models of ion doping, and models based on the Boltzmann transfer equation and Monte Carlo method [1,4,7] do not provide 100% reproducibility of the implanted profile. One can achieve of 5-10 % accuracy for three reasons [8-10]:

1. Models used for ID of silicon are formed by single-charge ions, and their channeling reduces the accuracy.

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2. Such models are not taken into account the effect of isoconcentration of oxygen and carbon impurities on the doping profile, although Si-plates are used in the mass production [10].

3. Absence of high-energy technology of ID and mask for it will not allow to change in a wide range the doping profile on depth of LSI-structures.

All this requires the improvement of existing models, which under certain conditions could be extended to implant with multi-charge high energy ions. The use of high-energy ID technology not only reduces the dose and time of doping, but also improves the accuracy of reproduction of implanted profiles [11].

The most common method of ion doping modeling is analytical approximation modeling. Its essence is that the coefficients of the model are determined by a given experimental profile. The impurity profile is defined by the function [7,8]:

$$C(y) = \frac{Qf(y)}{\int_0^\infty f(y)\,dy}, \qquad (1)$$

where Q is the number of implanted impurity, f(y) is the distribution function.

Most of the experimental data on the distribution of phosphorus, arsenic and antimony ions are well approximated by twin Gaussians. In this case, the concentration distribution is specified by two Gaussians with different dispersions for both the left and right distributions, and which are stitched along the modal run length R_m. The concentration distribution thus obtained has the form:

$$f(y) = \begin{cases} \exp\left[-\frac{(y-R_m)^2}{2\Delta R_{p2}^2}\right], & y < R_m \\ \exp\left[-\frac{(y-R_m)^2}{2\Delta R_{p2}^2}\right], & y > R_m \end{cases}. \qquad (2)$$

For the high-energy distribution, this expression is refined taking into account the dependence of the distribution parameters on the dose and energy of the ID, the thickness of the masking oxide, and the concentration of the isoconcentration impurity [12].

The profile of implanted boron is described more accurately by Pearson IV distribution:

$$f(y) = K\left[b_0 + b_1(y-R_p) + b_2(y-R_p)^2\right]^{\frac{1}{2b_2}} \times \exp\left[-\frac{b_1/b_2 + 2a}{\sqrt{4b_2b_0 - b_1^2}} arctg \frac{2b_2(y-R_p)+b_1}{\sqrt{4b_2b_0-b_1^2}}\right], \qquad (3)$$

where a, b_0, b_1, b_2, and K are the coefficients that determine the asymmetry, the profile excess, R_p is the projected range that determines the longitudinal straggle ΔR_p.

The use of high energy multi-charge B^{++}, P^{++}, As^{++} and Sb^{++} ions in LSI submicron technology [13,16] allows to increase both the energy E and the dose D_b of ions depending on the multiplicity of the ion charge n:

$$E = (U_{rec}+U_{acc})en,\ D_b = nD,$$

where U_{rec} and U_{acc} are rectified and acceleration voltages, respectively.

The projected range and longitudinal straggle are determined by their dependence on energy in the mathematical model of ID.

III. Calculations The Concentraton Profile of Boron Ions According Pearson Model

The longitudinal straggle ΔR_p and the scattering ΔR_{p1} are linearly dependent on the energy in an arbitrarily wide energy range E. Therefore, using all the existing nomograms to calculate these parameters for the degree of ionization of the ion, one can obtain nomograms for high-energy implantation. The distribution parameters of implanted boron B^+ and B^{++} accordingly Pearson model are presented in the Table I.

TABLE I. The parameters of the distribution profile of boron ions B^+, B^{++}

E_1, E_2, keV	10, 20	30, 60	50, 100	70, 140	100, 200	200, 400	300, 600	400, 800
R_{p1}, nm	40, 80	100, 202	164, 328	226, 452	310, 620	556, 1012	735, 1470	900, 1800
ΔR_{p1}, nm	28, 56	42, 84	57, 114	70, 140	84, 168	110, 220	116, 232	127, 254

As a rule, all ID processes to prevent channeling would be performed through a 100-200 Å oxide mask. In this case, the profile of the implanted silicon layer will be unchanged, but shifted to the Si-SiO_2 boundary by a value determined by the ratio of runs in oxide and silicon obtained by Czochralski process (CP) and zone melting (ZM) method [5,8,14]. As studies have shown using such silicon plates, the change of thickness W of activated layer is equal:

$$\Delta W = W_{act}\frac{R_p^2(Si_{ZM})}{R_p(SiO_2)R_p(Si_{CP})}. \qquad (4)$$

Studies have shown that the isoconcentration impurities of oxygen and carbon at $N \geq 5\cdot10^{16}$ cm^{-3} reduces the channeling effect and significantly improves the implantation distribution in its tail part. It should be noted that the impurities of oxygen and carbon also have a positive effect on the activation of implanted impurities.

Using multi-charge ions of boron, phosphorus, arsenic and antimony, the required profiles can be formed at different depths with high accuracy (< 3%). This ensures high reproducibility of electrophysical parameters in the formation of LSI-structures on the ID devices with individual treatment of the plates and shortens the cycle of their manufacture by 5-7 days. When using Si_{CP}-plates with an oxygen content more than 10^{17} cm^{-3}, it is possible to reduce the oxidation mask to 100 Å or to carry out ionic doping without it.

However, the transition of design norms beyond the limit of 130 nm within the traditional (considered) structure encounters physical limitations (Table 2).

TABLE II. PHYSICAL LIMITATIONS OF SUBMICRON SCALING

№	*Features*	*Limit*	*Reasons for restriction*
1.	The thickness of the oxide	2.3 nm	Carrier tunneling through oxide
2.	Depth of p–n-junctions	30 nm	Resistance of drain-source areas
3.	Channeling	$U_T = 0.25V$	Sub-threshold current
4.	Shallow drain-source areas	15 nm	Contact resistance
5.	Channel length	60 nm	Sub-threshold current
6.	Gate length	100 nm	Sub-threshold current

IV. METHODS FOR IMPROVING OF FIELD MOS-TRANSISTORS

The reduction of the threshold voltage, when the channel length decreases, is already a display of short-channel effects, which become an obstacle to reducing the size of transistor structures. To reduce the short-channel effects, changes in the profiles of alloying impurities are used both in the lateral and horizontal directions. Zones around weakly alloyed drain and source areas are created in the horizontal direction along the channel (Fig. 1). Particularly effective is multi-charge implantation in this regard. Non-homogeneous (retrograde) distribution of impurities is created with the help of the latter in the vertical direction. Shallow drain-source contacts are also formed by the retrograde multi-charge implantation of BF_2^{++} and PF_3^{++} radicals [15,17]. To ensure high breakdown voltages of the super-thin gate dielectric, silicon dioxide doped with rare earth metals (Ho, La) is used, which increases the dielectric permittivity from 3.7 to 10-12.

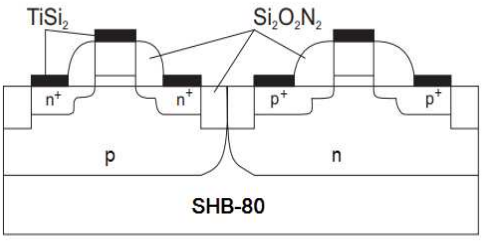


Fig. 1. Submicron CMOS structure with oxynitride isolation and spacers based on retrograde pockets.

The penetration of drain-source areas into the channel is the main cause of short-channel effects. However, it is not possible to eliminate them by simply increasing the concentration profiles of impurities the Si-substrate, since it increases the threshold current and reduces the mobility of charge carriers in the channel.

Here, the author implements a method of inverted channel effect when the threshold voltage increases with decreasing channel length. As we can see from Fig. 2 and Fig.3, this effect is achieved by creating retrograde haloes of implanted BF_2^{++}, PF_3^{++} ions around weakly alloyed drain-source regions. However, other alloying can be performed vertically, but preferably at an angle, for which the Si substrate is tilted by an angle of 20° to 80° with respect to the ion beam to direct it below the gate. Haloes are usually performed at the same lithography stage as the shallow weakly alloyed drain-source area. The implantation energy is quite high because multi-charge ions with the energy $E_n = E \cdot n$ are used that provides a deep occurrence of haloes.

After the formation of the oxynitride spacer and the drain-source areas, it is possible the subdoping of the channels to form built-in channels MOS transistors using also a radical multi-charge implantation.

Thus, multi-charge implantation was used in this structure to form retrograde pockets, haloes and channels, which prevent the formation of short-channel effects.

The concentration profiles of the impurity in the halo region, the weakly alloyed drain region and the pockets are shown in Fig. 2 and Fig. 3. The ionic doping in the pocket differs from the halo only in that it covers not only the weakly alloyed region but only part of it near the surface.

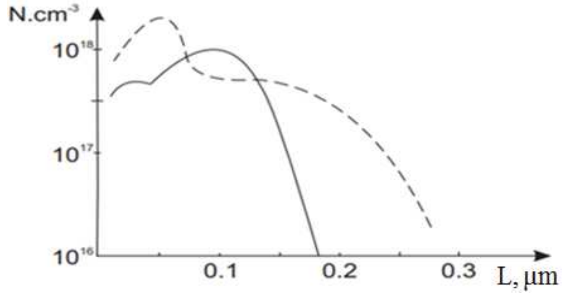


Fig. 2. Retrograde concentration profiles of impurities formed by the multi-charge implantation of BF_2^{++} in the drain-source areas and pockets of submicron MOS transistors.

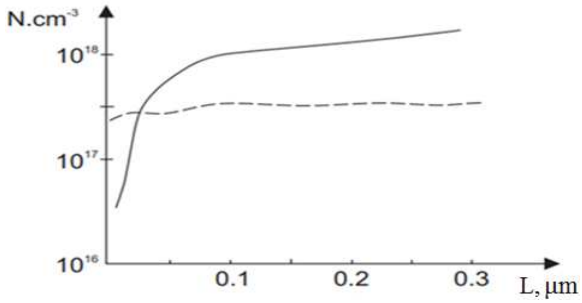


Fig. 3. Retrograde concentration profiles of impurities formed by the multi-charge implantation of PF_2^{++} in the drain-source areas and pockets of submicron MOS transistors.

The steep distribution of impurities in the pocket is created by the multi-charge implantation of AsF_3^{++} radicals for p-MOS transistors and BF_2^{++} for n-channel ones. Similarly, retrograde alloying with multi-charge implantation of polysilicon gates occurs, which replaces high-temperature diffusion alloying.

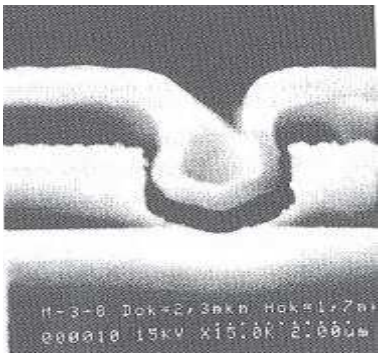
As is known, when using conventional methods of dry etching of dielectric films, the contact windows have vertical walls prior to their metallization. This, as a rule, leads to the breakage of metallized tires of the LSI layout.

The solution to this problem now is to obtain contact windows in the interlayer and interlevel dielectrics with a slope of the side walls $\theta \leq 65°$. For n-MOS LSI-structures [8,12,17], the most common method of reducing θ is high-temperature melting of phosphorosilicate glass, which is used to insulate polysilicon and aluminum tires. However, this method is not suitable for CMOS LSI-structures with two-level metallization. One can also use the combinations

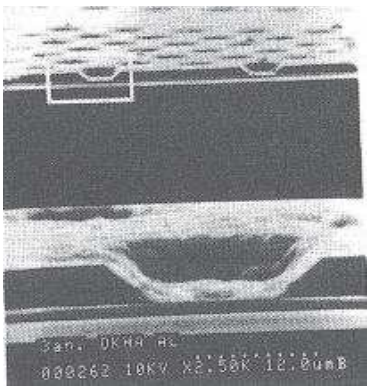
of wet and dry etching methods, when wet etching provides a profiling of window contact less 1.5 μm in size.

The most common method of obtaining profiled windows is the use of controlled erosion of the photoresist, that is, the reduction of the selectivity of the etching of the insulating layer relative to the photoresistive mask. Typically, this is achieved by introducing oxygen or oxygen compounds into the working plasma.

For CMOS LSI-structures, the original way of reducing the angle θ is to profiling of the contact windows by photoresist erosion or by spacer technology. This type of technology is shown in Fig. 4 a, b both for forming a hidden contact in the multi-level wiring and for profiling of contact window.



a



b

Fig. 4. Pollination of topology steps by SiO_2 film: a – deposited with high-conformity plasma chemical deposition; b – profile of the contact window after itc profiling.

IV. Conclusions

1. On the example of multi-charge implantation of B^+, B^{++} boron ions and molecular BF_2^+, BF_2^{++} ones a Pearson modification model was developed to form isotype p^+-p transitions through a thin gate dielectric of 10-30 nm in thickness by changing their charge, energy and implantation dose.

2. On the basis of this model, the concentration profiles of multi-charge implantation of phosphorus, arsenic and antimony on the paired Gaussian model are modeled, which qualitatively reflects the isotype n^+-n transitions through a thin incompatible gate of 10-30 nm in thickness.

3. It is found that the isotype p^+-p and n^+-n junctions formed in this way are an original solution to the formation of CMOS structures in modern silicon and gallium arsenide technology.

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