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Phosphorus concentration profile in silicon produced by means of the nuclear reaction $^{30}Si(p,\gamma)^{31}P$

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Abstract

A possibility to introduce phosphorus in silicon, different from direct phosphorus ion implantation, is discussed. The method is based on the nuclear reaction $^{30}Si(p,\gamma)^{31}P$ that occurs when a silicon sample is bombarded with energetic protons. It is shown that the pattern of the phosphorus concentration profile can be accurately controlled through an appropiate choice of the energetic characteristics of the proton beam. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The incorporation of foreign atoms in a material is very important in the microelectronics industry [1,2]. The traditional method to accomplish this is bombarding the target with ions of the doping species, which is called direct implantation. However, the passage of heavy atoms through the target produces several defects in the material. On the other hand, nuclear reactions induced by light projectiles have been used to measure the energy loss of protons [3] or the concentration of dopants [4].

Here we discuss the incorporation of phosphorus atoms in a target of silicon by means of the nuclear reaction $^{30}Si(p,\gamma)^{31}P$. Using this method, the dopant profile can be tailored by controlling the energetic characteristics of the proton beam in such a manner that nuclear reactions can be

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activated just at the desired depth. As a result of this process, it is possible to obtain phosphorus profiles with different shape, such as a homogeneous region or markers at several depths.

Section 2 shows briefly the formalism used to calculate the phosphorus depth concentration. In Section 3 we discuss the results obtained when several resonance energies participate in the process and finally, in Section 4, we present the main conclusions.

2. Model

When a silicon target is bombarded by an energetic proton beam the nuclear reaction $^{30}Si(p,\gamma)^{31}P$ occurs; in this process, by capturing a proton, the target nucleus ^{30}Si is transmutated into the excited nucleus $^{31}P^*$, which decays from the resonance level to lower levels or to the ground level by γ-ray emission, remaining as ^{31}P. Then as a final result of this process we have a silicon matrix doped with phosphorus atoms.

The nuclear reaction $^{30}Si(p,\gamma)^{31}P$ can occur only within small energy intervals, Γ_i (typical values are from 1 to 10^4 eV), around a few resonance energies, E_i. The relation between the proton energy, E, and the nuclear reaction cross section is given by the Breit–Wigner formula [5]. Taking into account that the spins of the proton and ^{30}Si nucleus are $\frac{1}{2}$ and 0, respectively, the nuclear reaction cross section, when several resonance energies are involved, is given by

$$\sigma(E) = \frac{\pi\hbar^2}{4ME}\sum_i \frac{\Gamma_i S_i(\mathrm{p},\gamma)}{(E-E_i)^2 + \Gamma_i^2/4}, \tag{1}$$

where M is the proton mass and $S_i(\mathrm{p}, \gamma)$ represents the strength of the resonance. The inset in Fig. 1 shows the nuclear reaction cross section, Eq. (1), as a function of the proton energy, calculated using

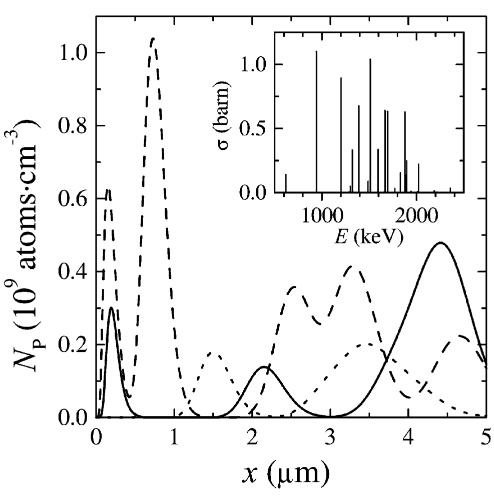

Fig. 1. Phosphorus depth concentration obtained for three energies of the proton beam: $\bar{E}_0$ = 1900 keV (– – –), 2000 keV (——) and 2100 keV (- - -). The values of ϕ and Γ_b are 10^{15} cm^{-2} and 1 keV, respectively. The inset shows the cross section corresponding to the nuclear reaction $^{30}Si(p,\gamma)^{31}P$, as a function of the proton energy.

available experimental data [6]. It can be seen that the nuclear reaction ^{30}Si(p ,γ)^{31}P occurs only for a discrete set of energies, and with different intensity.

In what follows, we will describe briefly the main features of this formalism, and we will apply it to the interesting case when several resonance energies participate in the doping process. The case of a single resonance energy was described in [7].

Let us consider a proton beam with an approximate Gaussian energy distribution

$$g(E_0) = \frac{2\sqrt{\ln 2}}{\sqrt{\pi}\Gamma_b}\exp\left[-\frac{4\ln 2(E_0-\bar{E}_0)^2}{\Gamma_b^2}\right], \tag{2}$$

where $\bar{E}_0$ is the average incident energy and Γ_b is the full-width at half-maximum (FWHM) of the distribution. Typical values of Γ_b are ~ 1 keV. When this proton beam bombards a silicon target, it is slowed down and when it reaches the resonant energies E_i it produces a number of phosphorus atoms per unit volume. This concentration is a function of the depth x and, for a proton dose ϕ, it is given by

$$N_P(x,\phi) = n_{Si}c\{1-\exp[-\phi\iint dE\, dE_0\, g(E_0)F(E_0-E,x)\,\sigma(E)]\}. \tag{3}$$

where $c = 0.031$ is the initial fraction of ^{30}Si present in natural silicon [5] and n_{Si} is the number of silicon atoms per unit volume. The distribution of protons that have an initial energy E_0 and suffer an energy loss $(E_0 - E)$ after a path length x, is given by the Landau–Vavilov distribution [8,9]

$$F(E_0-E,x) = \frac{1}{\delta\sqrt{2\pi}}\exp\left\{-\frac{[(E_0-E)-\bar{E}]^2}{2\delta^2}\right\} \tag{4}$$

with $\bar{E}$ and δ being, respectively, the mean energy loss and the energy loss fluctuation of a proton with an initial energy E_0, after travelling a path x. After some algebra, we obtain the phosphorus depth concentration,[1]

$$N_P(x,\phi) \simeq 1.57\frac{\pi\hbar^2 n_{Si}c\phi}{\sqrt{2\pi}M\Lambda(x)}\sum_i \frac{S_i(p,\gamma)}{E_i}\exp\left\{-\frac{1}{2}\frac{[\bar{E}_0-E_i-xS_p(\mathscr{E}_i)]^2}{[\Lambda(x)]^2}\right\}. \tag{5}$$

In the previous expression we have used that $\bar{E} = xS_p(\mathscr{E}_i)$ and $\delta^2 = x\Omega_B^2$; $S_p(\mathscr{E}_i)$ is the stopping power for a proton evaluated for the average energy $\mathscr{E}_i = (\bar{E}_0 + E_i)/2$, and $\Lambda(x)$ is defined as

$$\Lambda(x) = \sqrt{x\Omega_B^2 + \frac{\Gamma_b^2}{8\ln 2}}, \tag{6}$$

where Ω_B^2 represents the Bohr energy loss straggling [10], which is appropiated in this energy range. Eq. (5) shows how the phosphorus depth concentration depends on the parameters overline $\bar{E}_0$ and Γ_b that characterize the proton initial energy distribution.

[1] This expression corrects a misprint in Eq. (5) and Eq. (7) of Ref. [7].

3. Results and discussion

The phosphorus concentration profile is analyzed when several resonance energies are involved as the proton is slowed down in the silicon target. Without loss of generality, we particularize a proton beam with an energy around 2000 keV. In all the calculations that follow, we use a proton dose $\phi = 10^{15}\,\mathrm{cm}^{-2}$ and the stopping power values provided by SRIM [11].

Fig. 1 shows the phosphorus concentration as a function of the depth in the silicon target, Eq. (5), for three energies of the proton beam ($\bar{E}_0 = 1900$, 2000 and 2100 keV); in all the cases we have used $\Gamma_b = 1$ keV. It can be observed that small variations of the proton beam energy produces sizeable changes in the position, width and intensity of the phosphorus concentration profile. This is so because varying the proton beam incident energy, different nuclear reactions take place and at a depth that depends on the stopping power of the silicon target. If we focus on a particular resonance, we observe that the nuclear reactions are induced farther from the target surface when the proton energy increases, and only a single peak appears in the phosphorus profile.

In order to check the ability of this method to dope a sample with a controlled profile, we have investigated the possibility to obtain doped profiles with a layered structure, which is of interest in the microelectronics industry. Fig. 2 depicts the calculated phosphorus concentration profile obtained with a proton beam of $\bar{E}_0 = 2550$ keV (dotted line), $\bar{E}_0 = 2575$ keV (solid line) and $\bar{E}_0 = 2600$ keV (dashed line). In the three cases we obtain a doping profile with phosphorus markers at almost equidistant separations, but at larger depths for the larger incident proton energies. It is worth noting that a sequential bombardment of the silicon target using these three proton energies broadens the doped regions but maintains the structure, which is shown by a thick solid line in Fig. 2.

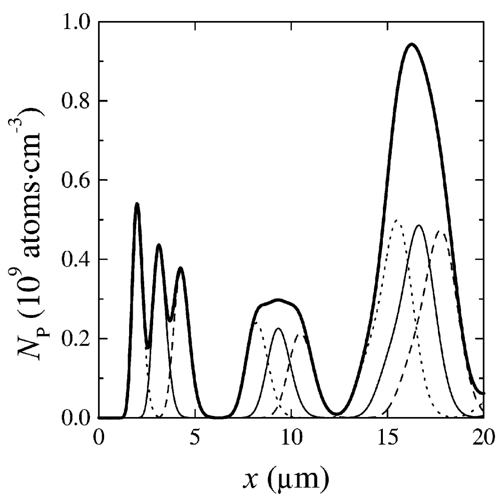

Fig. 2. Phosphorus depth concentration obtained after a proton beam of mean energy $\bar{E}_0$ bombards a silicon target: $\bar{E}_0 = 2550$ keV (- - -), 2575 keV (——) and 2600 keV (– –). The superposition of the three cases is indicated by a thick solid line. The dose and the FWHM of the proton beam are $10^{15}\,\mathrm{cm}^{-2}$ and 1 keV, respectively.

4. Conclusions

A method to incorporate phosphorus atoms in a silicon sample has been discussed, which is based on the transmutation of ^{30}Si atoms into ^{31}P by means of the nuclear reaction ^{30}Si(p,γ)^{31}P. It has been shown that the concentration profile of phosphorus atoms can be patterned choosing properly the energetic characteristics of the proton beam.

Although high proton doses should be needed to attain conventional phosphorus doping, the possibilities of new applications using low concentrations of dopants is a topic that remains open. Using the method discussed in this work, such concentrations can be obtained in a controlled manner if the proton dose is carefully controlled in order to produce detectable outcomes but to avoid damage effects in the target.

The method we have presented may be extended to other nuclear reactions and it may be of interest to the microelectronics industry.

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References

[1] Wang LK, Chuang CT, Li GP. Solid State Electr 1986;29:739.
[2] Bichsel H. Rev Mod Phys 1988;60:663.
[3] Kido Y, Hioki T. Phys Rev B 1983;27:2667.
[4] Pruppers MJM, Zijderhand F, Maessen KMH, Bezemer J, Habraken FHPM, van der Weg WF. Nucl Instr and Meth B 1986;15:512.
[5] Krane KS. Introductory Nuclear Physics. New York: Wiley, 1988.
[6] Endt PM. Nucl Phys A 1990;521:1.
[7] Abril I, Garcia-Molina R, Erokhin KM, Kalashnikov NP. Appl Phys Lett 1995;66:3036.
[8] Landau LD. J Phys USSR 1944;8:204.
[9] Vavilov PV. Zh Ekps Teor Fiz 1957;32:923. [Sov Phys JETP 1957;5:749].
[10] Bohr N. Mat Fys Medd Dan Vid Selsk 1948;18:8.
[11] Ziegler JF. SRIM. The stopping and range of ions in matter, Version 96.01.