Ultrashallow \(p^+-n\) junctions in silicon (100): electron-beam diagnostics of the surface zone

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Ultrashallow \(p^+-n\) junctions formed in silicon (100) under nonequilibrium impurity diffusion conditions are analyzed by electron-beam diagnostics of the surface zone using a probe of low- to medium-energy electrons. The energy dependence of the radiation conductivity is investigated, along with its distribution over the area of the \(p^+-n\) junction. This procedure can be used to determine the depth distribution (in the crystal) of the probability of separation of electron-hole pairs by the field of the \(p-n\) junction; the experimental results show that this distribution differs according to whether the kick-out mechanism or the dissociative vacancy mechanism of impurity diffusion is predominant as the basis of formation of the ultrashallow \(p^+-n\) junctions. Also reported here for the first time are the results of investigations of the distribution of secondary point centers formed near the boundary of the ultrashallow diffusion profile, which exert a major influence on the transport of nonequilibrium carriers. The data obtained in the study demonstrate the possibility of improving the efficiency of photodetectors, \(\alpha\)-particle detectors, and solar batteries constructed on the basis of ultrashallow \(p-n\) junctions. © 1998 American Institute of Physics.

1. INTRODUCTION

Recently it has been shown experimentally that ultrashallow (to 10 nm) doping profiles with a sharp boundary can be obtained in silicon single crystals by in-plane diffusion technology making use of the entrainment of impurity levels by excess fluxes of vacancies or native interstitial atoms generated by a silicon-oxide interface.\(^1\)\(^\text{–}^4\) The doping level and the spatial distribution of the injected impurity in such profiles depend on which nonequilibrium diffusion mechanism—kick-out or the dissociative vacancy mechanism\(^3\)\(^\text{–}^6\)—is predominant, and they are determined primarily by the diffusion temperature and the thickness of the initial oxide.\(^3\) Here we discuss the results of an experimental study of the influence of these factors on the properties of the resulting structures in the example of surface quantum-well \(p^+-n\) junctions in silicon (100). Our choice of working method is to probe the surface zone by low- to medium-energy electrons\(^7\) as a means of determining the depth distribution (in the crystal) of the probability of separation of electron-hole pairs by the field of the \(p^+-n\) junction.

2. PREPARATION OF ULTRATHIN \(p^+-n\) JUNCTIONS IN SILICON

The basic materials used in preparing the \(p^+-n\) junctions were single-crystalline \(n\)-type silicon (100) wafers of thickness 350 \(\mu\)m with resistivities of 1.0 \(\Omega\cdot\)cm, 5.0 \(\Omega\cdot\)cm, 20 \(\Omega\cdot\)cm, or 500 \(\Omega\cdot\)cm. In the initial stage of the process both sides of the wafer were oxidized in dry oxygen at 1150 °C. Windows of a desired geometry were then exposed in the oxide layer on the working side by photolithography, and \(p^+-n\) junctions were formed in the windows by the diffusion of boron from the gaseous phase after short time intervals (4 min). The diffusion temperature was varied during the investigations (800 °C, 900 °C, and 1100 °C), and so was the thickness of the surface oxide, in such a way as to facilitate simulation of the conditions of the kick-out\(^5\)\(^\text{–}^6\) and dissociative vacancy\(^5\)\(^\text{–}^6\) impurity diffusion mechanisms, which were induced by excess fluxes of native interstitial atoms and vacancies, respectively. The generation of primary defects responsible for the entrainment and drag of diffusing impurity atoms was maintained at a high level during diffusion by saturating the boron-containing gaseous phase with additional dry oxygen and chlorides. The technological cycle was terminated with the formation of ohmic contacts around the perimeter of the windows and on the opposite face of the wafer. The doping profiles were measured by secondary-ion mass spectrometry (SIMS).\(^3\)\(^\text{–}^8\)

3. ELECTRON-BEAM DIAGNOSTICS OF THE SURFACE LAYERS OF SILICON SINGLE CRYSTALS

To compare the properties of the surface zones of different samples, we measured the radiation conductivity excited in this zone by a focused electron beam, varying its energy \(E_p\) in the interval from 0.1 keV to 3.0 keV so as to smoothly vary the probing depth from 2 nm to 250 nm (Ref. 7). To separate the induced current from the dark current, we performed these measurements with sinusoidal modulation of the primary electron flux at a frequency of 1 kHz. Control tests using direct current confirmed that a steady-state radiation conductivity \(\gamma\) is well established at such frequencies. The computer-controlled electron beam scanned the target surface, permitting the radiation conductivity coefficient \(\gamma\) to
be measured at uniformly spaced points, so that images of this surface could be obtained in excited electrons at various energies $E_p$. In the case of area-inhomogeneous samples the set of raster images enabled us to pick out a working zone on the sample surface and to plot the experimental $g(E_p)$ curve for it. This curve, which is related to the spectral characteristic of the photoconductivity in a reverse-biased $p$–$n$ junction, can be described by the integral equation 

$$
\gamma(E_p) = \int_0^\infty \frac{g(E_p, x)}{\Delta E} f(x) \, dx,
$$

where $g(E_p, x)$ is the one-dimensional distribution function of the specific energy losses by primary electrons with respect to the depth $x$ in the silicon, $\Delta E$ is the average energy spent in the formation of one electron-hole pair, and $f(x)$ is the carrier collection function of the $p$–$n$ junction; this represents the fraction of electron-hole pairs, excited at a given depth $x$, that are separated by the field and contribute to the current in the external circuit.

Figure 1b shows an example of the $\gamma(E_p)$ curve for one of the samples (see inset) and the form of the carrier collection function reconstructed on the basis of this curve. The collection function, which is global parameter of the $p$–$n$ junction by definition and which completely determines its response to external ionizing radiation, depends on the conditions of transport and recombination of the excited carriers. In our case nonequilibrium carriers are generated for the most part directly in the charge zone of the $p$–$n$ junction. The behavior of $f(x)$ in this zone reflects the probability of the separation of electron-hole pairs by the field of the $p$–$n$ junction. This probability is determined primarily by the nonequilibrium carrier lifetime and the distribution of the electric field.

4. CHARACTERISTICS OF THE ULTRASHALLOW DIFFUSION PROFILES OF BORON IN SINGLE-CRYSTALLINE $n$-TYPE SILICON (100)

Figures 1–3 show the main results for samples formed at various diffusion temperatures $T_{diff}$ and thicknesses of the oxide layer ($d_{SiO_2}$). At $T_{diff} = 800$ °C diffusion takes place primarily by the dissociative vacancy mechanism, whereby boron atoms are entrained by excess fluxes of vacancies. When diffusion takes place at $T_{diff} = 1100$ °C, the kick-out