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Short Communication

On the mechanism of ultrasonic loading effect in silicon-based Schottky diodes

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ABSTRACT

The influence of ultrasonic loading on current–voltage characteristics of Mo/n–n^+–Si structures has been investigated. The research of Schottky barrier height variation has been carried out for various ultrasonic waves frequency (4.1, 8.4, and 27.8 MHz), intensity (up to 0.8 W/cm^2) and loading temperature (160–330 K). The obtained results have been analyzed on account of the dislocation nature of the interface patches and model of ultrasound absorption by dislocation kinks. The values of the kink diffusion activation energy $W_k = (90 \pm 10)$ meV and the frequency parameter $f_k = (3 \pm 2) \cdot 10^9$ Hz have been determined.

1. Introduction

Ultrasound is known to be effective tool for a semiconductor properties modification [1–8]. In the case of non-piezoelectric semiconductors, such ultrasound ability deals with an acousto-defect interaction. Thus ultrasonic waves (USWs) cause an atomic diffusion [1,2], a point defect rearrangement [3–5], an annealing of radiation defects [6–8], an reducing the concentration of recombination traps decorating the dislocations [9]. For instance, the ultrasound can residually [8–10] and reversibly [4,5,11] affect electrical properties of semiconductor barrier structures. In particular, the acoustically induced reversible modification of the barrier height and the ideality factor of the silicon Schottky diode have been observed [12].

The elastic vibration-defect interaction in semiconductors is investigated theoretically too (e.g., see [13,14]). The main mechanisms of ultrasonically induced effects are considered to be the change of population of impurity oscillator levels [13], the displacement of impurity atoms with respect to their surroundings [15], the local temperature increase by clusters of point defects [14], the dislocation absorption of ultrasound [10,16]. However to the best of our knowledge, very few experimental works have focused on investigation of dependencies of acoustically induced effects on USW parameters and ultrasound loading (USL) conditions. As a result, the complete theory of acousto-defect interaction in silicon is absent.

This article presents the result of experimentally investigation of the ultrasound influence on the electrical characteristic of the Mo/n–n^+–Si structure depending on an USL temperature as well as on the USW frequency and intensity. The results are analyzed by using Brailsford's theory of ultrasound – defect interaction [17].

2. Experimental and calculation details

The samples used in our experiments were 0.2μm thick n–Si:P epitaxial layer on 250 µm thick n^+–Si:Sb substrate. The substrate N_s and epi-layer N_d carrier concentration were $4.2 \cdot 10^{22}$ m^{-3} and $7.25 \cdot 10^{21}$ m^{-3} respectively. The square of molybdenum Schottky contact fabricated on the epi-layer surface was 7×7 mm^2.

The forward current–voltage (I–V) characteristics of the samples both with and without USL were measured in the temperature range from 160 to 330 K. In case of US loading, the longitudinal waves excited in the samples were 4.1, 8.4, and 27.8 MHz in frequency f_{US} and had the intensity of $W_{US} < 0.8$ W/cm^2. The I–V characteristics were measured in an hour after the USL start.

In order to avoid the effect of piezoelectric field on I–V characteristics, the piezoelectric cell was shielded and aluminum acoustic line was used. The more details about the experimental setup are presented elsewhere [12].

The data non-linear fitting were done by using the method of modified artificial bee colony [18].

3. Results and discussion

Fig. 1 shows some I–V–T characteristics that have been measured with and without USL. The double bumps within the

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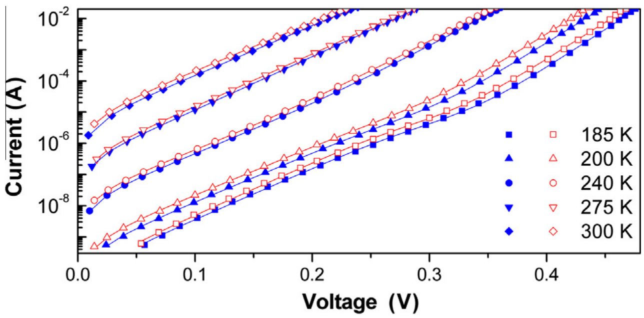

Fig. 1. *I–V* characteristics of Mo/*n*–Si Schottky structures measured at different temperature. The empty and filled marks correspond to structures with ($f_{US} = 27.8$ MHz, $W_{US} = 0.08$ W/cm^2) and without USL respectively. The lines are the fitted curves using Eq. (1).

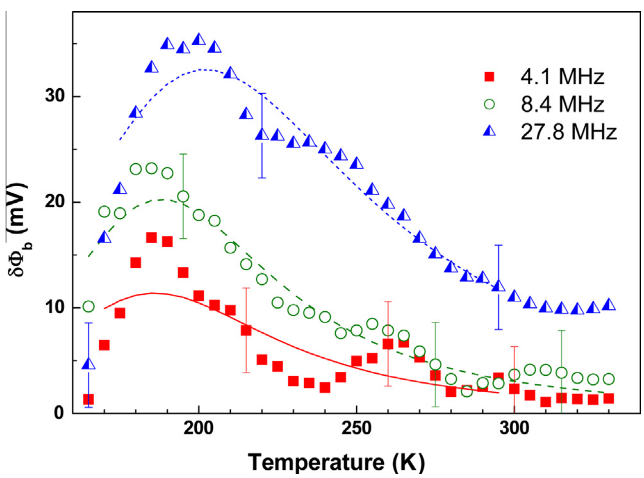

Fig. 2. Temperature dependencies of the acoustically induced barrier height variation for different f_{US} value. W_{US}, W/cm^2: 0.36 (4.1 MHz), 0.17 (8.4 MHz), 0.08 (27.8 MHz). The marks are the experimental results, the lines are the fitted curves using Eq. (4).

semi-log *I–V* characteristics can be interpreted by metal–semiconductor interface inhomogeneity [19]. It has been shown in Ref. [12], that the following expression can be used to fit the *I–V* characteristic

$$I = I_{0,1}\left[\exp\left(\frac{qV}{n_1 kT}\right) - 1\right] + I_{0,2}\left[\exp\left(\frac{q(V - IR_S)}{n_2 kT}\right) - 1\right], \tag{1}$$

where $I_{0,1}$ and $I_{0,2}$ are the saturation currents, n_1 and n_2 are the ideality factors, R_S is the series resistance. The second term represents the current flowing through patches and is negligible at a high temperature or/and at a high bias. $I_{0,1}$ deals with inhomogeneous Schottky barrier height (SBH) Φ_b:

$$\Phi_b = \frac{kT}{q}\ln\left(\frac{AA^* T^2}{I_{0,1}}\right), \tag{2}$$

where A is the diode area, A^* is the effective Richardson constant. It had been shown previously [12], that ultrasound affected patches current as well as n_1 and Φ_b values. But acoustically induced changing of Φ_b is most significant and we restrict ourselves to features of this effect only.

Fig. 2 shows the SBH variation ($\delta\Phi_b = \Phi_{b,0} - \Phi_{b,US}$, where $\Phi_{b,US}$ and $\Phi_{b,0}$ are the barrier height at the same temperature with and without USL, respectively) at different temperature and f_{US} values. It has been found, that (i) the barrier height variation under ultrasound action has been a non-monotonic function of temperature at all f_{US} value and (ii) the temperature of effect maximum slightly has increased when going to higher ultrasonic frequency. The SBH variation amplitude increases with the ultrasound intensity increasing and the dependencies at each temperature and frequency are close to a linear. This effect is illustrated by Fig. 3. Therefore, the following expression can be used:

$$\delta\Phi_b(f_{US}, T) = \beta(f_{US}, T) \cdot W_{US}, \tag{3}$$

where β characterizes USW energy, spent on the SBH variation, or, in other words, the efficiency of ultrasound influence on SBH.

It had been shown [12], that the SBH height variation under ultrasound action could be accounted for by the acoustically

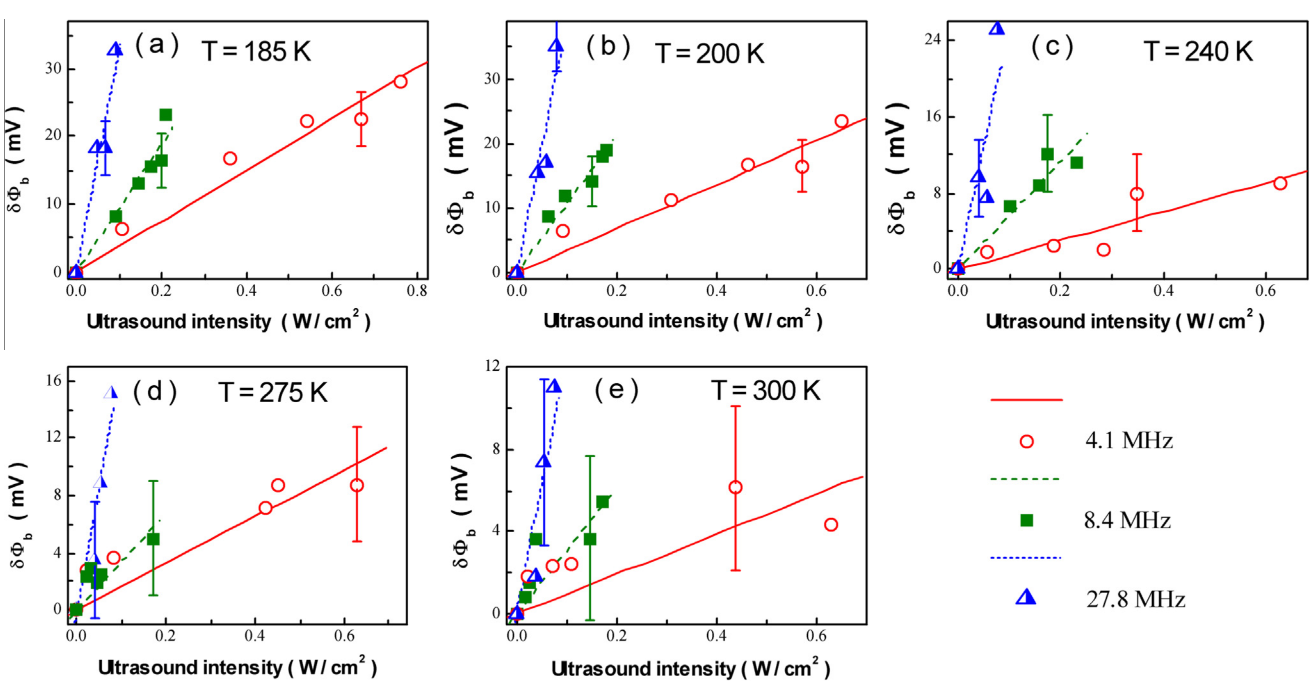

Fig. 3. Dependencies of the acoustically induced SBH variation on the ultrasound intensity. The marks are the experimental results, the lines are the fitted curves using Eq. (3).

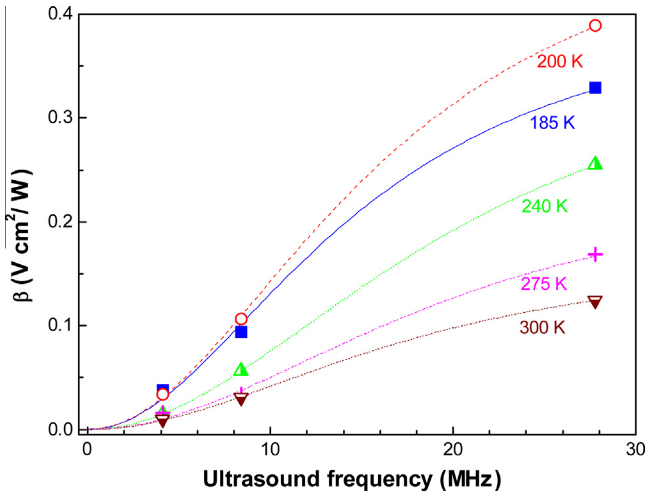

Fig. 4. Dependencies of the efficiency of ultrasound influence on SBH on frequency at different temperatures. The marks are the experimental results, the lines are the fitted curves using Eq. (4).

induced oscillation of patch. In our opinion, the misfit dislocations, that arisen due to doping difference of substrate and epi-layer, may be patches in structure under investigation. Thus, coefficient β must deals with the ultrasound absorption by misfit dislocations. On the other hand, the Brailsford's model of ultrasound absorption is known [17]. According to this model, dislocation is regarded as a sequence of segments connected by abrupt kinks. The ultrasound is absorbed due to the stimulated motion of kinks and the absorption coefficient α can be expressed as [17,20]

$$\alpha(f_{US}, T) \sim \frac{f_{US}}{T} \frac{(f_{US}/f_k)\exp\left(\frac{W_k}{kT}\right)}{1 + (f_{US}/f_k)^2 \exp\left(\frac{2W_k}{kT}\right)}, \tag{4}$$

where W_k is the kink diffusion activation energy, f_k is the frequency parameter, connected with the average length of dislocation segment.

We suppose that $\beta \sim \alpha$ and use Eq. (4) by taking W_k and f_k as the fitting parameters to fit the experimental temperature dependencies. The results are shown as the lines in Fig. 2. The good enough agreement of the experimental data with the fitting curves is observed. The values $W_k = (90 \pm 10)$ meV and $f_k = (3 \pm 2) \cdot 10^9$ Hz are determined.

It has been found that the β increases with ultrasound frequency increasing – see Fig. 4. This trend coincides with Brailsford's model prediction. We use Eq. (4) and value $W_k = 90$ meV to fit the β experimental frequency dependencies. The results are shown in Fig. 4.

Thereby model of ultrasound absorption, taken place due to the dislocation kinks motion, is able to interpret the temperature and frequency features of acoustic influence on SBH in Mo/n–n^+–Si structures.

4. Conclusion

The experimental investigation of features of reversible Schottky barrier height modification under ultrasound action has been carried out. The investigation has revealed that the efficiency of ultrasound influence non-monotonically depends on temperature in the range from 160 to 330 K and increases with acoustic waves frequency increasing. It has been found, that the SBH variation amplitude linearly depends on ultrasound intensity at $W_{US} < 0.8$ W/cm^2. It has been shown that the assumption about dislocation nature of the patches and Brailsford's model of ultrasound absorption can interpret the observed effects. Thus, ultrasound can be an effective tool for controlling metal–semiconductor structure characteristics.

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