High-frequency acoustic wave detection in Schottky diodes: theory consideration.

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Abstract

In this paper the theory of high-frequency acoustic signal detection by Schottky diodes is presented. Physically, the detection was found to be due to the quasi-static screening of the potential perturbation caused by the acoustic strain by charge carriers. The total charge required for screening changes with the value of strain at the edge of the semiconductor depletion region and metal-semiconductor interface giving rise to displacement current. The magnitude and frequency dependence of the electrical signals are analyzed for both piezoelectric and deformation potential coupling mechanisms. The obtained results are in good agreement with the recent experimental observations and suggest feasibility of high-frequency (up to terahertz band) acoustic wave detection provided that proper electrical measuring scheme is available.
INTRODUCTION

In recent decades acoustic techniques in solid state physics demonstrate serious progress, especially by moving to previously unattainable high-frequency band, up to a terahertz frequencies [1]. Considerable efforts in this direction, called often picosecond ultrasonics, are stimulated by the short-wavelength character of acoustic waves in this band, and, in some cases, efficient coupling of acoustic strain to electronic, optical, magnetic excitations in solid state. This allows application of high-frequency acoustic signals for testing and control of nanodimensional solid-state structures. From practical point of view, the most serious restriction of picosecond ultrasonics is the use of ultrafast (femtosecond) lasers for both excitation of acoustic signals and detection of its coupling to a solid-state nanostructure, usually with the use of pump-probe technique. In spite of considerable improvement of such lasers characteristics and growth of their availability, development of a robust electrically controlled picosecond acoustic technique would be an essential breakthrough in the field. Speaking about the high-frequency acoustic wave excitation, terahertz sasers could be a solution of the problem [2–4]. For detection purposes, several options are available. The superconductor based detectors are in use from 70th. The robust bolometers used to be widely employed for acoustic spectroscopy are currently less popular since, in contrast to optical methods, they are hardly sensitive to the spectrum of an acoustic signal. The superconductor contacts do possess spectral selectivity [5] but their fabrication is quite sophisticated. Semiconductor-based approaches are more preferable. A photo-electric acoustic wave detection by p-i-n diodes with a quantum well embedded into the i region demonstrated high efficiency, but, although based on electric current measurement, requires use of femtosecond laser for temporal signal sampling [6]. An alternative, also semiconductor-based, method using Schottky diodes has been demonstrated recently [7]. It is purely electrical and is based on induction of displacement current by propagating acoustic wave. Considering such factors as all-electrical detection principle, use of robust well-studied devices technology which can be integrated with various solid-state structures, possible room-temperature applications, this method looks an attractive candidate for wide use as high-frequency acoustic detector. In this paper the main physical principles of Schottky diode acoustic detection are considered theoretically in details. The developed model allows to address such issues as feasible magnitude of the electrical signal, fundamental restrictions on detectable acoustic signal fre-
FIG. 1. The schematics of the energy diagram of $n$-type Schottky diode with the used coordinate frame. $z = z_i$ corresponds to the metal-semiconductor interface. The insert shows the model electrical circuit which is used for the electrical detection of acoustic signals.

quency, possible ways of the diode structure optimization. The paper is organized as follows. In section I the expression for the accumulated electrical charge due to the acoustic strain perturbation is obtained for important cases of piezoelectric and deformation potential coupling. It is used then in section II for analysis of the electrical response of the Schottky diode. Then, the conclusions follow.

EXPRESSION FOR THE ACOUSTIC WAVE INDUCED CHARGE IN A DIODE

The energy diagram of the Schottky diode is shown in Fig.1 for particular case of n-doped semiconductor. We consider the range of external biases $V$, for which the Schottky barrier is much higher than temperature measured in energy units. In this case the electrical current is small and it is possible to assume that electron distributions in semiconductor and metal regions correspond to quasi-equilibrium and can be characterized by quasi-Fermi levels shifted by the value of electrical bias $eV$ assuming positive sign for the direct bias of the
diode. While an acoustic wave propagates through the structure, the related strain induces the potential acting on electrons. Such a potential can be described within the deformation potential model [8]. Redistribution of the charge carriers in this potential gives rise to the perturbation of the electric field in the system. In addition, in a piezoelectric semiconductor electric field is perturbed due to the lattice polarization induced by the acoustic wave. The perturbed potential $\delta \varphi$ satisfies the Poisson equation, which in one-dimensional limit, corresponding to an acoustic wave propagating along $z$-axis which is normal to the flat metal-semiconductor interface, is

$$\frac{d\delta \varphi}{dz} = \frac{e}{\varepsilon_s \varepsilon_0} \delta n + \frac{1}{\varepsilon_s \varepsilon_0} \frac{dP_z}{dz}, \tag{1}$$

where $\delta n$ is perturbation of the electron concentration, $\varepsilon_s$ and $\varepsilon_0$ are the dielectric constant of the semiconductor and the absolute permittivity, and $P_z$ is the $z$-component of the piezoelectric polarization. The important assumption we are going to use is that all perturbations caused by the acoustic wave are much slower than the electron relaxation processes in both metal and semiconductor. The latter can be characterized by the dielectric relaxation time $\varepsilon_{s,m} \varepsilon_0 / \sigma$, where $\sigma$ is conductivity and $\varepsilon_m$ is the lattice dielectric permittivity of metal. Such time is usually within subpicosecond band for semiconductor and even shorter for metal. Thus, we may use a quasi-static approach determining $\delta n$ while dealing with sub-terahertz acoustic waves. This means that at any time instant the electron density perturbation is the same as in the case of static nonuniform strain distribution corresponding to this particular time. Specifically, dropping the time dependence for brevity, in the linear approach for semiconductor region $z < z_i$ we have:

$$\delta n(z) = e(\delta \varphi(z) - U_{DP}(z) / e - \delta V_s) \frac{dn_s}{dE_F}, \tag{2}$$

where $n_s(E_F)$ is the electron concentration dependence on the Fermi energy, $U_{DP}$ is the deformation potential energy of electrons, and we allow perturbation of the semiconductor reference potential, $\delta V_s$, caused by the acoustic wave. Note, that the value of the derivative in right hand side of Eq.(2) depends on coordinate. Analogously, in metal, $z > z_i$, we have

$$\delta n(z) = e(\delta \varphi(z) - U_{DP}(z) / e - \delta V_m) \frac{dn_m}{dE_F}. \tag{3}$$

With Eqs.(2,3), the Poisson equation becomes a linear inhomogeneous differential equation. It is convenient to perform its solution separately for $z < z_i$ and $z > z_i$, applying then the
boundary conditions at \( z = z_i \). Using standard variation of constants method and taking into account that \( \varphi(z = -\infty) = \delta V_s, \varphi(z = \infty) = \delta V_m \), we obtain

\[
\delta \varphi(z) = \delta V_s + c_s \phi_{s2}(z) + \frac{\phi_{s2}(z)}{w_s} \int_z^{z_i} dz' \phi_{s1}(z') \left( k_s^2(z') U_{DP}(z')/e - \frac{1}{\varepsilon \varepsilon_0} \frac{dP_z}{dz'} \right) + \tag{4}
\]

\[
\phi_{s1}(z) \int_{-\infty}^{z} dz' \phi_{s2}(z') \left( k_s^2(z') U_{DP}(z')/e - \frac{1}{\varepsilon \varepsilon_0} \frac{dP_z}{dz'} \right), \text{ for } z < z_i
\]

\[
\delta \varphi(z) = \delta V_m + c_m \phi_{s2}(z) - \frac{\phi_{m2}(z)}{w_m} \int_{z_i}^{z} dz' \phi_{m1}(z') k_m^2(z') U_{DP}(z')/e - \frac{\phi_{m1}(z)}{w_m} \int_{z_i}^{\infty} dz' \phi_{m2}(z') k_m^2(z') U_{DP}(z')/e, \text{ for } z > z_i.
\]

Here \( c_s \) and \( c_m \) are constants, \( k_{s,m}^2 = e^2 dn_{s,m}/dE_F(\varepsilon_{s,m} \varepsilon_0)^{-1} \), and \( \phi_{m1,2} \) are fundamental solutions of the homogeneous versions of equations for \( \delta \varphi \):

\[
\frac{d\phi_{s1,2}}{dz^2} = k_s^2(z) \phi_{s1,2} \text{ for } z < z_i \tag{5}
\]

\[
\frac{d\phi_{m1,2}}{dz^2} = k_m^2(z) \phi_{m1,2} \text{ for } z > z_i
\]

These functions are selected such that \( \phi_{s2}(-\infty) = 0, \phi_{m2}(\infty) = 0 \) and Wronskians in Eq.(4) are \( w_{s,m} = \phi_{s,m1} \phi'_{s,m2} - \phi'_{s,m1} \phi_{s,m2} \).

The constants \( c_s \) and \( c_m \) are determined via the boundary conditions at \( z = z_i \), requiring continuity of potential and electrical induction. Then, it is straightforward to calculate the perturbation of the accumulated charge, \( \delta Q \):

\[
\delta Q = \varepsilon \varepsilon_0 S \int_{z_i}^{\infty} dz k_m^2(-\delta \varphi(z) + U_{DP}(z)/e + \delta V_m), \tag{6}
\]

where \( S \) is the diode cross-section. After some algebra from the expressions for the potential we obtain

\[
\delta Q = C \left( \delta V - V_{PZ}(z_i) + \int_{-\infty}^{z_i} dz G_s(z) (V_{DP}(z) + V_{PZ}(z)) - \int_{z_i}^{\infty} dz G_m(z) V_{DP}(z) \right), \tag{7}
\]

where we introduced the effective potential due to the deformation potential acousto-electric coupling \( V_{DP} \equiv -U_{DP}/e \), potential induced due to poizoelectric action of the acoustic wave \( V_{PZ} \) such that \( V'_{PZ} = P_z/(\varepsilon_s \varepsilon_0) \), the kernel functions

\[
G_s(z) = \frac{1}{\phi_{s2}(z_i)} \phi_{s2}(z) k_s^2(z), \tag{8}
\]

\[
G_m(z) = \frac{1}{w_m} \left( \phi_{m1}(z_i) \phi'_{m2}(z_i) - \frac{\varepsilon_s}{\varepsilon_m} \phi_{m2}(z_i) \phi'_{m1} \right) \frac{1}{\phi_{m2}(z_i)} \phi_{m2}(z) k_m^2(z).
\]
and the diode capacitance \( C = \varepsilon_s \varepsilon_0 S / L_{\text{eff}} \) with

\[
L_{\text{eff}} = \frac{\phi_{s2}(z_i)}{\phi_{s2}'(z_i)} - \frac{\varepsilon_s \phi_{m2}(z_i)}{\varepsilon_m \phi_{m2}'(z_i)}.
\]

(9)

In Fig. 2 we plot the spatial dependence of the kernel function \( G_s \) calculated for GaAs Schottky diodes with doping \( 10^{17} \text{ cm}^{-3} \) and \( 10^{18} \text{ cm}^{-3} \) and temperatures \( 10K \) and \( 300K \). The steady-state potential profile and the screening parameter were determined with the standard approach assuming low value of the diode current \([9]\). As we see, the charge is controlled by the perturbation near the edge of the depletion layer. This result is expectable: indeed, the used boundary conditions assume no acoustic perturbation for \( z = -\infty \). In this case although variation of strain inside the spatially uniform portion of semiconductor leads to charge redistribution, it does not change the total charge in it. Only if strain changes near the inhomogeneous region near the edge of the depletion layer, the total charge experiences the perturbation.

For comparison, we show the kernel function for a rough model of step-like dependence of \( k_s \), where it is set to zero in the depletion region and to the value of the bulk semiconductor to the left of its edge, assumed to be infinitely sharp. The approximation allows analytical determination of \( G_s \). As we see, for semiconductor this model is not very good, especially at room temperature where depletion region edge is not well-defined. However, it is good for the metal region since here any energetic perturbation is much less then the Fermi energy. As a result, for metal we can use the analytical expression for \( G_m \), which is \( G_m = k_m \exp(-k_m(z-z_i)) \) for \( z > z_i \). It is important to mention useful normalization conditions, which hold for any distribution of potential in the diode:

\[
\int_{-\infty}^{z_i} G_s(z) dz = 1,
\]

(10)

\[
\int_{z_i}^{\infty} G_m(z) dz = \xi_m \equiv \frac{1}{w_m} \left( \phi_{m1}(z_i) \phi_{m2}'(z_i) - \frac{\varepsilon_s}{\varepsilon_m} \phi_{m2}(z_i) \phi_{m1}'(z_i) \right)
\]

Let us discuss the in some details the deformation potential and piezoelectric couplings. For semiconductor-contribution this is straightforward. The deformation coupling describes the shift of the bottom of the conduction band minima. Its specific form depends on the crystal symmetry and the momentum position of the conduction band \([10]\). In any case, \( V_{DP} \) is proportional to strain. Below, to be specific, we will provide expressions for the case of GaAs with \( z \)-axis parallel to its [111] crystallographic direction and longitudinal acoustic
FIG. 2. The kernel function $G_s$ for GaAs Schottky diodes with doping level $10^{17}$ cm$^{-3}$ and $10^{18}$ cm$^{-3}$ and different temperatures. $z = 0$ corresponds to the metal-GaAs interface, i.e. $z_i = 0$. For comparison, the results for model step-like spatial dependence of $k_s$ are shown.

wave propagating along $z$. In this case

$$V_{DP} = \frac{E_1}{e} u_{zz},$$

where $E_1$ is the deformation potential constant and $u_{zz}$ is the only present component of strain.

The piezoelectric potential is determined by the strain-induced piezoelectric polarization. For the mentioned geometry and acoustic wave polarization we obtain

$$V_{PZ} = \frac{2\varepsilon_{14}}{\sqrt{3}\varepsilon\varepsilon_0} u_z,$$

where $\varepsilon_{14}$ is the piezoelectric constant of a cubic material and $u_z$ is the only present component of displacement in the considered longitudinal acoustic wave. As we see, the piezoelectric effect induces charge not only because of charge redistribution, but also due to direct induction of potential (the second term in the brackets of Eq. (7)).

It is worth to mention that for the case of different crystallographic orientation, crystal symmetry or acoustic wave polarization the general structure of the expressions for defor-
formation and piezoelectric potentials remains the same with the former proportional to strain and the latter proportional to displacement. Of course, in some cases some contributions vanish. For example, in GaAs there is no piezoelectric coupling for acoustic wave of any polarization propagating along [100] direction; deformation potential in this case is absent for transverse wave.

For the metal region consideration of the coupling of acoustic wave to electrons is more complicated than for semiconductor. This is because the deformation potential in a metal is considered as a perturbation of electron spectrum in some momentum point near the Fermi surface. Therefore, this value is, strictly speaking, momentum dependent. While considering screening, a momentum-averaged value is introduced to determine the charge perturbation \[ E_m \] \[ u_{zz} \]. Its dependence on the strain components is determined by the symmetry of the metal Fermi surface. In fact, the corresponding constants are hardly known. This is because experiments on electron transport or ultrasound attenuation in metals provide \textit{screened} value of electron-phonon coupling averaged in a specific way \[ \Pi \]. In the following, we will use in metal

\[ V_{DP} = \frac{E_m}{e} u_{zz}, \]  

keeping in mind that the effective constant \( E_m \) has specific value dependent on the metal crystallographic orientation (for metal single crystals) and acoustic wave polarization. By the order of magnitude, one can expect \( E_m \) to be about few electronvolts.

It is worth mentioning that in general we should not discard piezoelectric-like coupling in metal. It is usually done while considering electron scattering by phonons since efficient screening in metals cancels any macroscopic potential. However, the magnitude of the space charge induced under the screening does not vanish. In particular, this is seen from the expression for \( G_m \), which provides finite value for the induced charge regardless of large value of \( k_m \). In the following we do not include piezoelectric contribution in metal into consideration since no info is available of its presence and strength. However, one has to keep in mind that high-frequency acoustic wave detection by Schottky diode could reveal possible piezoelectric-like coupling in metals. In principle, it can be distinguish from the deformation potential, since, similar to the semiconductor, the it should be proportional to the displacement rather than strain.
DETECTION OF THE ACOUSTIC WAVE BY THE DIODE

Naturally, the signal induced by an acoustic wave passing through the diode depends both on its intrinsic characteristics and the properties of the electrical circuit which includes the Schottky diode. We consider simple model circuit consisting of the diode and series resistance $R$ (see the insert of Fig.1). Using Eq.(7) we can easily obtain equation for $\delta V$:

$$\frac{d\delta V}{dt} + \frac{\delta V}{RC} = \frac{dS}{dt}$$

$$S = \left( V_{PZ}(z_i) - \int_{-\infty}^{z_i} dz G_s(z) \left( V_{DP}(z) + V_{PZ}(z) \right) + \xi_m V_{DP}^{(m)}(z_i) \right),$$

where the right hand side can be considered as a source caused by an acoustic wave, smallness of the screening length in the metal is taken into account, and superscript $(m)$ indicates the deformation potential in the metal. The particular form of the acoustic signal depends on the kind of the acoustic source. In high-frequency band the most popular one is a bipolar strain pulse generated with the use of picosecond ultrasonics technique [1]. Alternatively, quasi-monochromatic acoustic waves can be produced by semiconductor superlattices illuminated by femtosecond laser pulses [1] or sasers [2–4]. Since in the linear response regime any acoustic signal can be presented as a plane wave superposition, in Eq.(14) we switch to the frequency domain and obtain

$$\delta V_\omega = \frac{1}{1 + i(\omega RC)^{-1}} S_\omega.$$  (15)

The intrinsic detection properties of the diode are reflected by the frequency dependence of $S_\omega$. In fact, it is determined by the spatial broadening of the kernel function $G_s$. Assuming the plane-wave strain, we obtain

$$S_\omega = -i \tilde{V}_{PZ} \left( 1 - J_s \exp(i\theta) \right) + \xi_m \tilde{V}_{DP}^{(m)} - \tilde{V}_{DP}^{(s)} J_s \exp(i\theta),$$  (16)

where $\tilde{V}_{PZ}$ and $\tilde{V}_{DP}^{(s,m)}$ are the amplitudes of the piezoelectric and deformation potentials (with the superscript labeling semiconductor and metal contributions). For the specific case of [111]-oriented semiconductor (Eqs.(11,12,13)) we have $\tilde{V}_{PZ} = 2e_{14}u_{zz}^{(0)} s \left( \sqrt{3} \varepsilon_s \varepsilon_0 \omega \right)^{-1}$ and $\tilde{V}_{DP}^{(s,m)} = E_{s,m} u_{zz}^{(0)}/e$, where $s$ is sound velocity and $u_{zz}^{(0)}$ is the strain amplitude. In Eq.(16) the overlap integral is introduced:

$$J_s \exp(i\theta) = \int_{-\infty}^{z_i} dz G_s(z) \exp(i\omega z / s).$$  (17)
FIG. 3. The calculated overlap $J_s$ for various doping levels and temperature.

The calculated frequency dependence of $J_s$ is shown in Fig. 3. As it is expected, $J_s$ is suppressed for frequencies corresponding to the acoustic wavelength smaller than the spatial localization length of the kernel $G_s$. The frequency dependence of $\theta$, which is not shown in a graph, reflects the phase shift of the acoustic signal at the edge of the depletion layer and at the metal-semiconductor interface and corresponds roughly to $2\pi$ variation for frequency increase about 90 and 26 GHz for doping $10^{18}$ and $10^{17}$ cm$^{-3}$, respectively.

If piezoelectric coupling is present in the structure, it commonly exceeds the deformation one for frequencies below a hundred gigahertz. For separate analysis of the piezoelectric contribution it is convenient to introduce the value $J_s^{(PZ)} \equiv |1 - J_s \exp(i\theta)|$. The frequency dependence of $J_s^{(PZ)}$ is shown in Fig. 4. Naturally, it shows resonances corresponding to in-phase perturbation at the edge of the semiconductor depletion region and metal-semiconductor interface. Positions of these resonances can be easily predicted since the piezoelectric contribution to the diode response is determined by the parameters of semiconductor only, which are usually well-known.

It is worth to mention a special case of piezoelectric coupling and relatively low frequency acoustic wave, for which the acoustic wavelength is larger than both the broadening of $G_s$
and the thickness of the depletion layer. Here, $S$ becomes proportional to strain. So, for the particular case of Eq. (12) we have $S = 2\varepsilon_{14}u_{zz}L_{eff}(\sqrt{3}\varepsilon_0\varepsilon_s)^{-1}$. If, in addition, if $(RC)^{-1}$ exceeds considerably the characteristic acoustic frequency, $\delta V = S$. In other words, the electrical signal measures directly the value of strain in near-interface region. For doping $10^{18}$ cm$^{-3}$, this approach can be valid for frequency up to several tens of gigahertz.

In diodes where piezoelectric coupling is absent, for example those employing non-piezoelectric semiconductors, like Si or Ge, or grown along certain crystallographic directions, like [001] GaAs, the situation is different. The resonances are expected in this case as well, but their location is difficult to predict because of unknown value of the effective deformation potential constant in metal.

For higher frequencies the deformation potential coupling is most efficient. In addition, as we see from Fig. 3 the semiconductor contribution is suppressed for high frequencies. However, the metal contribution persists for any realistic frequency. This means that the actual frequency restrictions are set by the ability of high-frequency electronics to measure the high-frequency electric signals.
Summarizing the obtained results we can conclude that the acoustic wave detection by Schottky diodes can be described by a simple model where electrical response of the diode is caused by the displacement current induced by electrons screening the strain-induced perturbation. The actual upper frequency limit is set by the parameters of the current-registering equipment rather than internal diode properties due to the fast electronic response and small screening length in metal contact of the diode. On the other hand, the semiconductor-side signal contributions are efficient, for common diode structures for frequencies below few hundreds of gigahertz. These results will be an important guide for interpretation of the measured electrical diode response to an acoustic perturbation as well as optimization of the Schottky diode acoustic wave detectors.

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