# High-velocity surface acoustic waves in diamond and sapphire with zinc oxide film

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We report two numerical examples of high-velocity surface acoustic waves, a type of surface waves which was recently shown to exist if a thin film is present on a surface. The nonattenuated high-velocity surface waves have been found in diamond orientation with Euler angles (0°,0°,45°) and sapphire orientation with Euler angles (0°,−20.3°,0°), with zinc oxide film. In diamond, the wave has ''symmetric'' structure with displacement in the symmetry plane while, in sapphire, the example of a ''nonsymmetric'' solution is presented. The numerical analysis has confirmed that, in both examples, the wave has a true surface nature, with one-partial structure in a substrate. [S0003-6951(99)03945-5]

In past years surface acoustic wave (SAW) devices found wide application in communication systems. Increasing operating frequencies in such systems caused a strong demand for high-velocity SAWs. Utilization of leaky surface acoustic waves (LSAW)[1] and, in particular, recently found high-velocity LSAWs,[2] creates new possibilities for the development of high-frequency SAW substrates. Though LSAWs exist in any crystal, in general these waves are strongly attenuated due to the leakage of acoustic energy into the bulk of the crystal. The attenuation coefficient tends to zero if the LSAW degenerates into a pure bulk wave, called in this case ''exceptional,'' or into a true SAW, due to vanishing contributions of inhomogeneous or homogeneous (bulk) partial waves to the LSAW solution.

A method of search for exceptional bulk waves was previously reported.[3] In particular, it was shown that, in contrast to quasishear exceptional waves, which can be found in any crystal, quasilongitudinal bulk waves, usually propagating with higher velocity, can only be exceptional in a few crystals, with sufficiently strong acoustic anisotropy. Considering true SAWs, such solutions can occur on a low-velocity LSAW branch,[4,5] which is confined in the velocity interval $(V_S, V_F)$, while on a high-velocity LSAW branch located in the interval $(V_F, V_L)$ such solutions are not allowed to exist. Here $V_S$, $V_F$, and $V_L$ are the threshold velocities of slow and fast quasishear and quasilongitudinal bulk waves, respectively. Thus, a high-velocity LSAW can turn into the nonattenuated solution only in some crystals, in which the quasilongitudinal bulk mode can be exceptional.

Recently, we reported that the deposition of a thin film on the substrate surface can result in propagation of a nonattenuated high-velocity surface acoustic wave (HVSAW).[6] The energy of such a wave is localized near the surface and in general it behaves like a true SAW. A numerical example of the HVSAW was found in silicon carbide (SiC), hexagonal 6H polytype, with zinc oxide (ZnO) film, when the boundary surface was parallel to the (001) plane in both substrate and film materials. Unfortunately, due to the incomplete published set of elastic constants for SiC, we were not able to predict accurately the thickness of the ZnO film providing low-loss propagation of the HVSAW.

In this letter, we report two other numerical examples of HVSAWs found in diamond and sapphire with ZnO films. The calculations were made with the published material constants for ''film ZnO''[7] (point symmetry class 6 mm), diamond[8] *(m3m)* and sapphire[9] $(\bar{3}m)$. Both substrate materials analyzed are attractive for high-frequency applications due to higher acoustic wave velocities, compared to the typical values in other SAW substrates. Since, the symmetries of the diamond and sapphire do not allow piezoelectric properties, ZnO films are often used to introduce piezoelectric coupling to surface waves in such substrates.

Figure 1 shows the simulated velocities and attenuation coefficients of high-velocity LSAWs in diamond, as functions of ZnO film thickness-to-wavelength ratio $h/\lambda$. The interface and top surface of the layered structure ZnO/diamond are parallel to the (001) planes of diamond and ZnO. The propagation direction in diamond is [110] while in ZnO it is not defined, due to the transversal isotropy of acoustic properties in a hexagonal crystal. Using the Euler angles, the diamond orientation is defined as (0°, 0°, 45°).

The coordinate system *X, Y, Z* is chosen with *Z* axis as an outward normal to the boundary plane and *X* axis parallel to the propagation direction. The sagittal plane *XZ* is a plane of material symmetry for diamond and ZnO. Consequently, the shear-horizontally (SH) polarized partial waves are uncoupled in both materials and the mechanical displacement of the LSAW is localized in the sagittal plane: $\mathbf{u}=(u_1,\ 0,\ u_3)$. In the substrate only two partial waves are involved, one of which is bulk. The latter is responsible for the leakage of energy and hence the LSAW attenuation. The contribution of the bulk partial wave tends to zero when the normalized ZnO thickness $h/\lambda$ approaches the value 0.042. At this point, in the substrate the wave has a single partial wave component, whose mechanical displacement exponentially decreases with the depth: $\mathbf{u}_i=\mathbf{u}_o \exp(3.236z/\lambda)$. The calculated velocity of this wave is 13 846 m/s when the top surface is metallized. The calculation shows that the HVSAW solution disappears as the propagation direction deviates from [110]. We

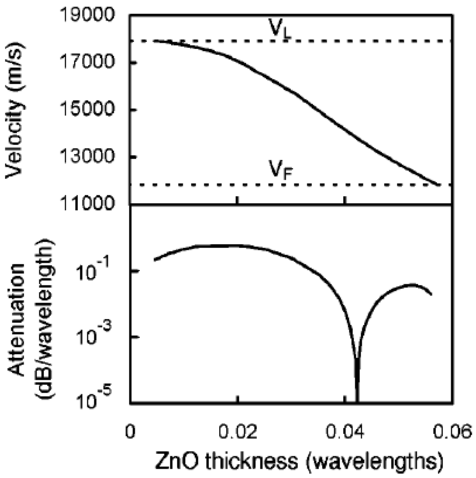

FIG. 1. Velocity and attenuation coefficient of high-velocity leaky waves in diamond, Euler angles $(0^\circ,0^\circ,45^\circ)$, with ZnO film, as functions of film thickness. $V_L$ and $V_F$ are threshold velocities of quasilongitudinal and fast quasishear bulk waves, respectively.

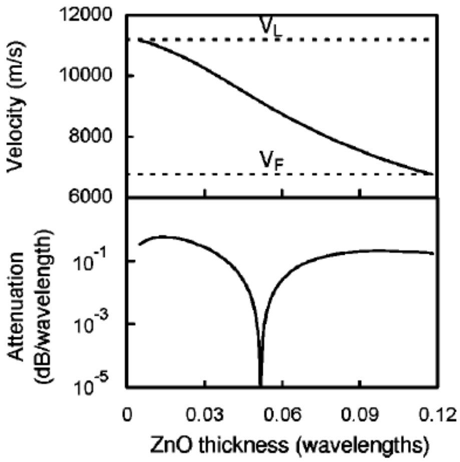

FIG. 3. Velocity and attenuation coefficient of high-velocity leaky waves in sapphire, Euler angles $(0^\circ,-20.3^\circ,0^\circ)$, with ZnO film, as functions of film thickness.

also verified the existence of HVSAWs if the propagation direction in diamond is [100]. Though in this case the sagittal plane is also a symmetry plane, no HVSAWs were found.

The careful numerical investigation of the wave structure has shown that the real and imaginary components of the complex amplitude coefficient associated with the bulk partial wave change the signs simultaneously. Hence, the HVSAW is a true SAW. A recent theoretical study[10] has confirmed the possibility of existence for nonattenuated high-velocity surface waves in layered structures. The ''symmetric'' HVSAW type, the example of which is presented above, has been considered. This type is characterized by the sagittal plane parallel to symmetry planes of the substrate and film materials. At first sight, the existence of HVSAWs in a more general ''nonsymmetric'' case, with coupled SH component of the displacement vector, looks problematic because it requires two complex amplitude coefficients to simultaneously vanish.

However, numerical studies of layered structures on low symmetry substrate materials, such as sapphire with a ZnO film, with the sapphire orientation defined by the Euler angles $(0^\circ,\theta,0^\circ)$ were able to locate a LSAW with attenuation less than $10^{-5}$ dB/$\lambda$. In practice, such a wave can be considered nonattenuated.

To clarify the nature of this wave, numerical analysis of the LSAW structure in the vicinity of the minimum attenuation point was performed. Since the SH component of the displacement is present for all partial waves in the substrate, the LSAW is usually composed of three partial waves, two of which are bulk waves. We analyzed the behavior of the two complex amplitude coefficients $C_{1,2}$ responsible for the contribution of the bulk waves. In the two-dimensional space $(\theta,\ h/\lambda)$ we found numerical solutions to the equations $\mathrm{Re}(C_i)=0$, $\mathrm{Im}(C_i)=0$, $i=1,2$. The resulting four ''zero lines'' plotted in Fig. 2 pass through the same point, $\theta=-20.3^\circ$ and $h/\lambda=0.0516$, which means that at this point the wave has a true SAW structure. The calculated velocity for this wave is 9154 m/s, when the top surface is metallized. With a slight variation of elastic constants used for calculation, the true SAW solution found does not disappear but moves to another point in the space $(\theta,\ h/\lambda)$.

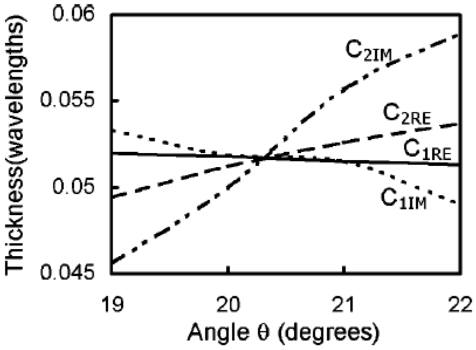

FIG. 2. ''Zero lines'' for real and imaginary parts of amplitude coefficients $C_{1,2}$ associated with two bulk partial waves in LSAW propagating in sapphire, Euler angles $(0^\circ,-\theta,0^\circ)$, with ZnO film, as functions of angle $\theta$ and film thickness.

The characteristics of the LSAWs propagating in the orientations of sapphire with the Euler angles $(0^\circ,\ -20.3^\circ,\ 0^\circ)$ are shown in Fig. 3 as functions of normalized ZnO film thickness. Figure 4 shows the displacement components versus depth in the same orientation for $h/\lambda=0.0516$. A remarkable feature of this example is that the SH component, $u_2$, does not vanish. As a result, the SH-polarized partial waves are present in a film, even though the wave remains nonattenuated.

Though HVSAWs need further theoretical analysis, especially the nonsymmetric type, the presented examples clearly demonstrate that a high symmetry of the substrate and film materials is not a necessary condition for the exis-

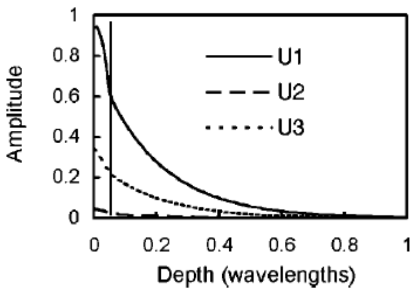

FIG. 4. Displacement components vs depth in sapphire, Euler angles $(0^\circ,-20.3^\circ,0^\circ)$. ZnO film thickness is 0.0516 wavelengths.

tence of such waves, and apparently they can be found in many layered structures.

In conclusion, we have reported two numerical examples of high-velocity surface waves propagating without attenuation in diamond and sapphire substrates when a ZnO film of certain thickness is deposited on the substrate surface. These waves exist due to the film presence and are characterized by one-partial wave structure in a substrate and pure exponential decay of mechanical displacement with depth. The existence of surface waves with high propagation velocity can be very useful for high-frequency applications. Finally, like the common SAW, HVSAWs can exhibit strong piezoelectric coupling.

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