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Ring waveguides for gigahertz acoustic waves on silicon

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We demonstrate a ring resonator for gigahertz surface acoustic waves (SAWs) consisting of a Ge waveguide on a silicon chip. SAWs generated by interdigital transducers on a section of the waveguide are guided over a curved path and detected by a second interdigital transducer. The structure of the GHz waveguide modes mapped using high resolution interferometry compares well with elastic calculations. The acoustic propagation properties as well as the potential applications of these semiconductor-based resonators are discussed. © 2014 AIP Publishing LLC.

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Light guiding by narrow waveguides (WGs) has triggered the remarkable advances in integrated optics during recent years. Similar to light, acoustic waves (in the form of surface acoustic waves, (SAWs)) can also be guided along linear WGs on the surface of a chip. One interesting question is whether GHz vibrations can also be efficiently guided along curved paths, so as to act as efficient acoustic actuators as well as interconnects for information transmission and processing. Potential applications for these guided beams include high-performance ring acoustic filters,1 actuators for nanomechanical2 and micro-fluidic elements, advanced acousto-optic elements,3 as well as conveyor belts for electronic excitations4,5 and single-phonon quanta.6

Although linear SAW WGs have been reported for several years,7–9 there have been so far only very few demonstrations of acoustic guiding along curved paths on planar structures. Here, two main challenges have been faced. The first is the complex structure of surface acoustic modes (as compared to their optical counterparts), which consist of both longitudinal and transverse field components with anisotropic propagation properties. The second are the material combination constraints required to ensure the high contrast between the acoustic properties of the core and cladding WGs regions needed for total internal reflection. So far, only two approaches have been applied to guide SAWs along a closed loop on a planar substrate, both using metal layers. In the first, SAW beams are directed along a closed path using acoustic reflection gratings.1,9 This approach does not require a WG. In the second, SAW guiding is achieved with a WG core consisting of a low velocity metal film10 or metal grating11,12 deposited on a “fast” substrate.

In this letter, we present an alternative approach for guiding GHz SAWs based on Ge ridge WGs fabricated on a silicon wafer. The approach explores the high contrast between the acoustic properties of Ge and Si, which provides the mode confinement required to guide SAWs along WGs with small radius of curvature. These WGs employ crystalline materials, thus enabling low acoustic absorption at high frequencies, and their fabrication is fully compatible with the Si CMOS technology.13,14 The SAW guiding by curved WGs is first demonstrated by elastic calculation for the WG structures. In the experimental studies, Rayleigh SAWs are generated on a section of a WG racetrack (cf. Fig. 1(a)) by high-frequency interdigital transducers (IDTs) placed on a piezoelectric ZnO island. The waves are then focused by an acoustic horn into a narrow WG section, which guides them along a circular path towards a second IDT. SAW propagation is investigated by radio-frequency (rf) techniques as well as by interferometric mappings of the SAW field, which confirm the predicted mode structure. These results thus demonstrate the feasibility of the integration of WG phononic elements on Si CMOS chips.

The ring delay lines of Fig. 1(a) were fabricated on Si (001) wafers containing a $d_{\text{Ge}}=1\ \mu\text{m}$-thick intrinsic Ge film epitaxially grown by the reduced-pressure chemical vapor deposition process described in detail in Ref. 15. IDTs oriented along the $x'parallel[110]$ surface direction were photolithographically fabricated on a layer stack consisting of a 350 nm-thick piezoelectric ZnO and a 50 nm-thick SiO$_2$ films deposited on the Ge film by magnetron sputtering. The single-finger IDTs were designed for an acoustic wavelength $\lambda_{\text{SAW}}=2.8\ \mu\text{m}$; they are 160 $\mu\text{m}$ long and consist of an array of equally spaced $\lambda_{\text{SAW}}/4$ wide and 50 $\mu\text{m}$-long Ti/Al/Ti fingers (with thicknesses of 10/30/10 nm). We have also fabricated ring delay lines with floating electrode unidirectional transducers16 (FEUIDTs), which emit preferentially along one direction. The latter have the same length and aperture as the split-finger ones and a periodicity of 7 $\mu\text{m}$. The ridge WGs were photo-lithographically defined by plasma etching the Ge film in the regions indicated in Fig. 1(a): Fig. 1(b) shows an optical micrograph of the final structure. The acoustic horns17–19 couple the wide SAW beams generated by IDTs to the narrow WG sections, which have a circular section with radius of curvature of 140 $\mu\text{m}$. We will present here results for narrow WGs with a width of 3 $\mu\text{m}$. Three types of structures were investigated: (i) short rings (WG$^{(i)}$) with 685 nm-long horn and single-finger IDTs for $\lambda_{\text{SAW}}=2.8\ \mu\text{m}$; (ii) similar structures, but with longer (1363 $\mu\text{m}$) horns (WG$^{(ii)}$), and (iii) rings as in (i), but with FEUIDTs (WG$^{(iii)}$). As in a ring laser, the SAWs in the latter circulate preferentially in one direction. Note that the narrow WG sections have the same dimensions in all structures.

In order to demonstrate acoustic waveguiding in the Ge/Si structures, we used a finite element approach20 to calculate
the elastic modes of a circular WG. The calculations were carried out for a ring WG with bending radius $R_c = 50 \lambda_{SAW}$ ($\lambda_{SAW} = 2.8 \mu m$) using a cylindrical unit cell with coordinates $(r,\phi,z)$ (cf. inset of Fig. 2) delimited by $|r - R_c| < \lambda_{SAW}$, $|\phi| < \lambda_{SAW}/(2R_c)$, and $-2\lambda_{SAW} < z < d_{Ge}$. Periodic boundary conditions were applied to the two surfaces at $\phi = \pm \lambda_{SAW}/(2R_c)$ to emulate the propagation in a circular structure. We have used isotropic elastic constants for Si and Ge averaged over the in-plane crystallographic directions.21 Figures 2(a) and 2(b) show the displacement patterns for the lowest frequency eigenvectors confined in the WG. The acoustic energy mainly concentrates at the upper edges of the WG. This behavior is consistent with a stronger localization of the lowest frequency modes at the regions of large surface area due to the lower acoustic velocity near a surface. In fact, the lowest frequency modes in straight and wide (i.e., with widths $\gg \lambda_{SAW}$) ridge WGs consist of two degenerate edge modes, each propagating along one of the upper edges of the ridge. For narrow WGs (widths $\lesssim \lambda_{SAW}$), the two edge modes intermix to form the modes with anti-symmetric [cf. Fig. 2(a)] and symmetric displacement patterns [cf. Fig. 2(b)] with respect to the plane perpendicular to $r$ passing through the center of the WG. The frequency of the anti-symmetric mode is slightly lower (by $\sim 3\%$ in Fig. 2) than the one of the symmetric. Due to the symmetric arrangement of the coupler in Fig. 1(a), however, waves impinging from the horn coupler are expected to couple preferentially to the symmetric mode. By the same token, an anti-symmetric mode resulting from the scattering of a symmetric wave within the WG (e.g., by defects) will neither be efficiently converted to a Rayleigh SAW at the WG output nor detected by the receiving IDT.

Before experimentally addressing the acoustic mode patterns, we probe SAW propagation via the acousto-electric response of the ring delay lines. The rf scattering reflection ($s_{11}$) and transmission ($s_{21}$) parameters for delay lines $WG^{(s)}$ and $WG^{(su)}$ are compared in Fig. 3. The single-finger IDTs of
WG(s) have a pronounced resonance at $f_{SAW} = 1.11$ GHz. The velocity obtained from the IDT resonance frequency and period agrees very well with the one of 1.117 GHz calculated for SAWs propagating along the [110] surface direction of the Ge/SiO$_2$/ZnO layer stack on (001)Si. The $s_i$ resonance for $WG^{(su)}$ corresponds to the excitation of the second harmonic of the FEUIDTs with $\lambda_{SAW} = 3.5 \mu$m. The measured and calculated resonance frequencies are in this case also very close (0.91 GHz and 0.923 GHz, respectively).

The rf transmission ($s_{21}$) spectra in Fig. 3 displays oscillations resulting from the interference between the acoustic signal propagating along the WG and the electromagnetic cross-talk captured by the detection electronics. The period of the oscillations $\Delta f = 2\nu_{SAW}/\nu_{WG}$, where $\nu_{WG}$ is the WG perimeter, yields the average SAW group velocity $\nu_{SAW}$ in the closed ring. The ratios $\nu_{SAW}/\nu_{WG}$ ($\nu_{SAW} = \lambda_{SAW} f_{SAW}$) are equal to 0.84 and 0.87 for the WGs with $\lambda_{SAW} = 2.8$ and $3.5 \mu$m, respectively. The effects of the electromagnetic cross-talk can be suppressed by recording $s_{21}$ spectra using a network analyzer with Fourier transform capability, as shown by the curves labeled $s_{21}$ in Fig. 3. The spectral shape of these curves reproduces reasonably well the sinc-function frequency response expected for the IDTs. Furthermore, a closer examination of the weak oscillations superimposed on the $s_{21}$ curves reveals that they now have a frequency periodicity $\Delta f = f_{SAW}/\nu_{WG}$ (cf. inset of Fig. 3(b)). These oscillations are due to the interference of acoustic waves arriving after different round trips at the detection IDT.

The impulse time response determined from the Fourier transform of $s_{11}$ and $s_{21}$ spectra yields further information about SAW propagation in the rings (cf. Fig. 4). The echo in $s_{11}$ (Fig. 4(a)) at $\tau_{WG} = \nu_{SAW}/f_{SAW} (i = s, su, l)$ arises from SAW reflection at as well as transmission through the second transducer. The main peaks in $s_{21}$ at delays $m\tau_{WG}^i/2, (m = 1, 3, 5)$ correspond to echoes with $m$ transit times between the IDTs, respectively. Finally, the echo $\tau_{WG}^i$ for $WG^{(su)}$ in Fig. 4(a) arrives at twice the SAW transit time through the long horn and arises from reflection at the horn ends connected to the narrow WGs. The corresponding reflections for the short rings (denoted $\tau_{WG}^i$) appear as shoulders at short delays. These reflections give rise to weak replicas of the main peaks, some of which are indicated by curved arrows in the diagrams.

The SAW amplitude reduces with the number of passes $\tau/\tau_{WG}^i$ around the rings, as summarized in Fig. 5. The signal decays at rates of 12 dB for $WG^{(su)}$ ($\lambda_{SAW} = 3.5 \mu$m) and 16 dB per round trip for $WG^{(s)}$ and $WG^{(l)}$ (both with $\lambda_{SAW} = 2.8 \mu$m). This behavior is consistent with a stronger scattering probability for modes with shorter wavelengths.

The ring delay lines studied here are intrinsically lossy due to SAW absorption by the IDTs. In order to address the loss mechanisms associated with SAW propagation, we have mapped the amplitude of the vertical surface displacement ($\delta z$) along the WGs using a scanning Michelson interferometer. Figures 1(c) and 1(d) and Figs. 1(e) and 1(f) display, respectively, one-(1D) and two-dimensional (2D) $\delta z$ profiles recorded on the sections of $WG^{(su)}$ indicated in Fig. 1(a) while exciting only the lower FEUIDT (i.e., IDT$_1$) of the delay line. Due to electromagnetic interference (as in the $s_{21}$ spectra of Fig. 3), the measured $\delta z$ signal corresponds to the surface displacement for a fixed SAW phase. The period of the fast oscillations corresponds, therefore, to the SAW wavelength. The thick lines superimposed on the 1D profiles are guides indicating the spatial dependence of the average $\delta z$ values. The preferential emission direction of FEUIDT$_1$ along $+x'$ accounts for the higher $\delta z$ values on its right [Fig. 1(d)] than on its left side [Fig. 1(c)]. Furthermore, the compression of the SAW beam width by the horns becomes apparent in the $\sim 2$ times increase of $\delta z$ as one approaches the entrance of the narrow WG sections. Finally, similar 1D profiles recorded at the output of the narrow WG sections (not shown) indicate a SAW amplitude reduction typically ranging from 30% to 50% (depending on sample), thus showing that losses in these sections constitute the main attenuation mechanism in the ring structures.

The 2D $\delta z$ maps of Figs. 1(e) and 1(f) show that the SAW remains confined within the structured Ge horn and narrow WG sections with little leakage to the Si substrate. Leakage gives rise to the weak wave pattern on the
surrounding Si areas. The oscillations in the horn region of Fig. 1(f) yield directly the SAW wavelength, which slightly reduces within the narrow WG sections due to the lower SAW velocity. More important, the profiles within the narrow WG sections (as well as in the horns) are symmetric, thus demonstrating that the vibration mode corresponds to the symmetric mode of Fig. 2(b).

The losses within the WG are attributed to scattering at imperfections such as rough ridge edges or defects, which induce mode interconversion or leakage to the substrate. One example is given by the defect visible on optical micrographs and marked as $D$ in Fig. 1(e), which leads to a significant reduction of the mode amplitude. These losses can be eliminated by improving the fabrication process.

In conclusion, we have demonstrated that GHz SAWs can be guided along curved paths by narrow ($\lambda_{\text{SAW}}$/24) Ge WGs on a Si substrate. Ring delay lines using these WGs show the implementation of several functionalities such as acoustic generation, detection, concentration, and guidance, thus opening the way for integration of GHz phononic components on a Si chip.

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10A. Maznev, Ultrasonics 49, 1 (2009).
21The calculations were performed with a Si (Ge) density of 2330 kg/m$^3$ (5323 kg/m$^3$), Young’s modulus of 185 GPa (103 GPa), and Poisson ratio of 0.28 (0.26).
22Other than the isotropic results in Fig. 2, these calculations for planar structures took into account the full elastic tensor of the layers.