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SAW Tags for the 6-GHz Range

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***Abstract*—The possibility of using 6-GHz frequencies for passive SAW tags is discussed. An example of an inline 6-GHz SAW tag design is presented. Supposing that an ultrawide frequency bandwidth $B = 775$ MHz can be used, the tag dimensions can be significantly reduced and the loss of reflected response remains at an acceptable level of around 50 dB. The devices were manufactured using E-beam lithography and, probed on wafer, show performance close to predicted, including the loss level of approximately 55 dB. The possibility of high-throughput manufacturing by combining nano-imprint and e-beam lithography is discussed.**

I. Introduction

Usually SAW tags are designed to operate in the 2.45-GHz ISM band [1]. The reading distance of the tags is proportional to the wavelength, whereas the number of codes is dependent on the frequency band used. Therefore, going to higher frequencies has advantages and disadvantages: wider bands are available but at the cost of shorter reading distance and increasing technological problems. In this paper, we study the feasibility of SAW tags at much higher frequencies than SAW tags used thus far. The unlicensed 5.65 to 6.425 GHz industrial frequency band is available in some countries for remote access applications [2]. For RFID applications, this ultra-wideband (UWB) frequency range would have obvious advantages. First, this band is much larger than the widely used 2.45-GHz ISM band ($B = 775$ MHz versus 82.5 MHz) and thus allows us to reduce the chip and antenna sizes and to increase antenna gain. Second, rather high levels (up to 1 W) of interrogation signals are permitted [2] in combination with high antenna gain, which can compensate the reduction of reading distance resulting from the short wavelength. Although the SAW propagation loss strongly increases at these frequencies, some reduction of the reflection response losses can be achieved because of the significantly shorter duration of coding pulses and shorter distance between them. The objective of this work is to study the feasibility of SAW tags at this frequency range via numerical simulations and on-wafer measurement of experimental devices produced according these simulations.

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II. Design of 6-GHz SAW Tag

The design of the 6-GHz SAW tag was presented at the 2013 IEEE Ultrasonics Symposium in Prague [3]. Here, we briefly summarize the results.

The test structure for the 6-GHz SAW tag was designed with the help of FEMSAW software [4]. It is important that this software includes all 2-D effects, such as bulk scattering of SAW on very short reflectors, typical in SAW tags. Such reflectors may scatter part of the incident SAW energy into the bulk, comparable with the reflected energy [5]. The tag contains an ordinary IDT consisting of $N_0 = 15$ aluminum electrodes (with metallization coefficient $m/p = 0.5$ and pitch $p = 0.313$ μm), and 7 weighted reflectors (start reflector + 5 code reflectors + end reflector). The number of fingers and the metallization coefficients were optimized to get

- uniform amplitudes of the code reflected peaks, and
- the start and end reflectors, having fixed positions, must give responses about 3 dB stronger than the code reflectors.

The optimization procedure [6] begins from reflectors situated at the far end from the IDT and is based on the fact that if you add one more reflector between the IDT and existing reflectors, the relative level of responses from the already existing reflectors will not change, but all their levels will decrease slightly. This allows easy alignment of the level of the added reflector to previous ones.

This procedure, repeated many times with FEMSAW simulation, gave the variable number and normalized width of open-circuited Al strips: $N_j = (2; 1; 2; 2; 3; 4; 7)$; $m/(2p) = (0.225; 0.3; 225, 0.25; 0.225; 0.225; 0.2525)$.

The thickness of electrodes and reflective strips is assumed to be equal to $h = 40$ nm ($h/\lambda \approx 0.064$). The distance between the IDT and the start reflector is 1 mm (corresponding to approximately 0.5 μs of initial delay). The reflectors are arranged periodically with a 50 μm gap between them with an acoustic aperture of $W = 70$ μm.

For a more precise evaluation of a real tag response, the Gaussian-type weighted interrogating RF pulse has been modeled with central frequency $f_0 = 6037.5$ MHz, duration $\Delta t = 1.3$ ns, and −3-dB bandwidth ~775 MHz (fractional bandwidth $\Delta f_{-3\mathrm{dB}}/f_0 \approx 0.13$); see Fig. 1.

The simulated time-domain response of the tag (in decibels, Fig. 2) consists of two edge-calibrating pulses

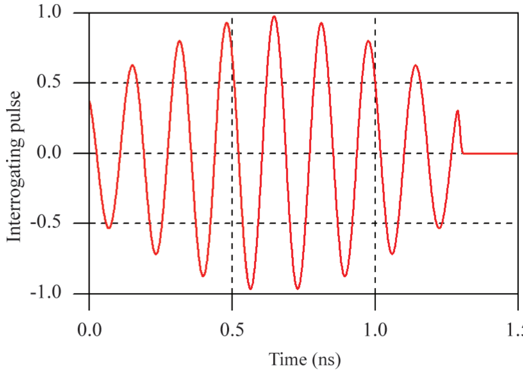


Fig. 1. Simulated interrogating pulse.

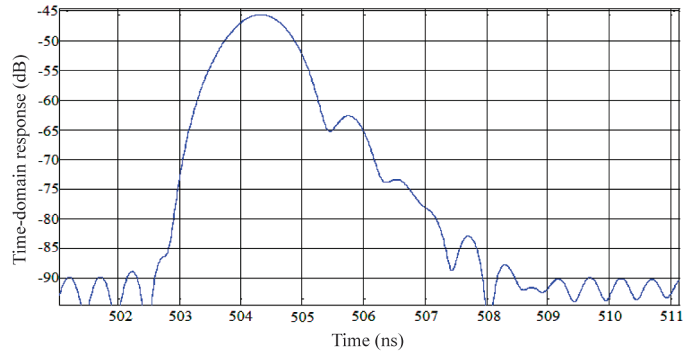


Fig. 3. First peak of the tag response.

and five coding pulses (Fig. 2). A series inductor of $L_S = 2$ nH, resulting from bonding wire inductance, is taken into account, also slightly improving the IDT matching with the assumed 50-Ω antenna. Note that the parasitic peaks after the seventh pulse appear because of multiple internal reflections of acoustic waves within reflecting delay line. In real SAW tags, similar pulses are partially suppressed because of the nonperiodic distribution of the coding reflectors within the acoustic tracks.

The duration of the first pulse, measured at the −3-dB level, is about $\Delta t \approx 1.3$ ns (Fig. 3), close to the expected value, but the total width is more than doubled because of the pulse interaction with the IDT and the reflector. In practice, to reduce the intersymbol interaction, a guard zone of $4\Delta t$ will be used between the peaks.

Another procedure for estimating losses is also possible. We can use the fast Fourier transform after gating in time one response peak and compare its spectrum to the spectrum of the interrogation pulse. Variation of the transfer loss is expected inside the passband for different spectral components: we estimate a loss level between 43 and 47 dB for the first peak in Fig. 2.

III. Experimental Results

Fig. 4 shows the SAW device chip in real proportions. The chip size is 2.0 × 0.94 mm, which is comparable to typical dimensions of an RF SAW filter. This small size corresponds to approximately 4000 devices per 100-mm

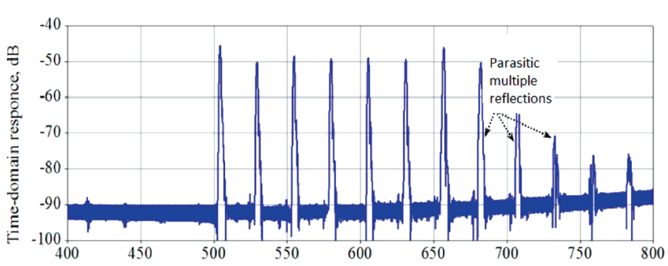


Fig. 2. Time-domain response of a tag to the interrogating RF pulse in Fig. 1.

(4-in) wafer, which in mass production should reduce the price of device to a level comparable to that of RF SAW filters. We have fabricated 100 SAW prototypes using electron beam lithography on a 100-mm (4-in) lithium niobate 128° cut substrate. First, the substrate is spin coated with zep520A (Zeon Chemicals LP, Louisville, KY) followed by a deposition of a thin 20-nm Al layer. The Al layer acts to avoid charging of the nonconducting substrate. Then, e-beam writing is performed using a state-of-the-art JEOL JBX-9500 (JEOL Ltd., Tokyo, Japan) and sequentially developed using standard wet development methods. Finally, 50 nm of Al is deposited and lift-off is performed, leaving the Al in the desired SAW ID-tag pattern, as seen in Figs. 4(a) and 4(b).

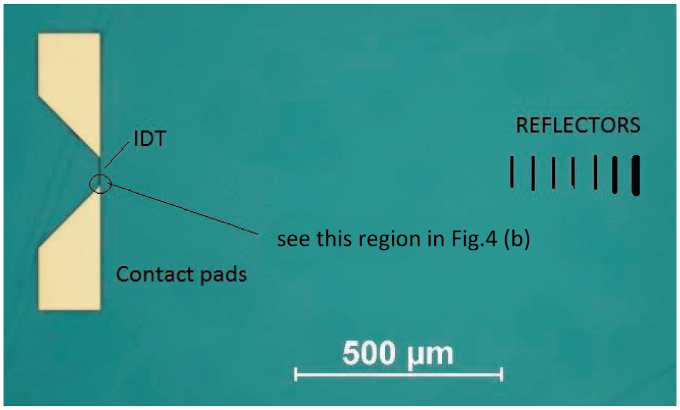
We have used pure Al as the electrode material without an adhesion layer and, probably because of that, the yield was rather poor; however, several devices are functioning as expected. The performance of one of the best devices probed on wafer is shown in Figs. 5 and 6. Figs. 5(a) and 5(b) show that, as designed, our transducer has an impedance reasonably close to 50 Ω.

Fig. 6 shows the measured impulse response on a decibel scale. One can see that the results are extremely close to the simulation (Fig. 2). The only visible difference is that the coding reflections are slightly weaker: 55 dB instead of the expected 50 dB loss.

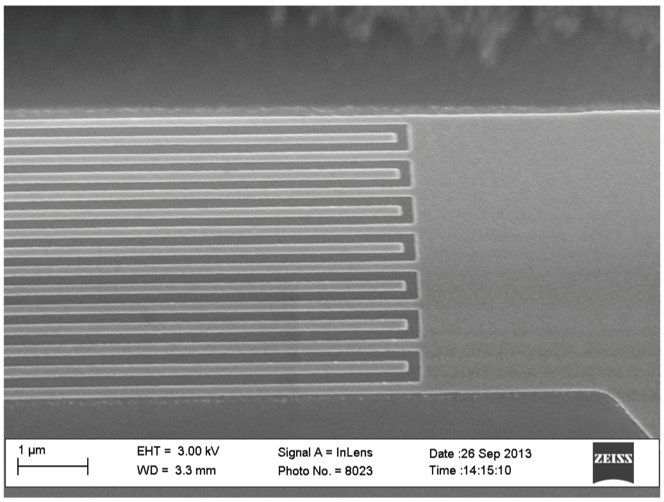
IV. Discussion and Conclusions

The feasibility to develop RF SAW tags with rather good performance in the 6-GHz frequency range has been proved theoretically and experimentally. With a narrow reflected pulse of about 1.3 ns duration (at −3-dB level, Fig. 3), the tag's insertion loss (depending on the initial delay) reaches an acceptable level of 50 to 55 dB. This insertion loss is comparable with the losses of SAW tags operating in the 2.45-GHz ISM band [6], [1].

In current prototype device, all coding reflectors were situated periodically, but in real tags, their position will code the ID number. Actually, we have only a dozen electrodes which are used for coding. The IDT and the start and end reflectors always remain the same. We consider

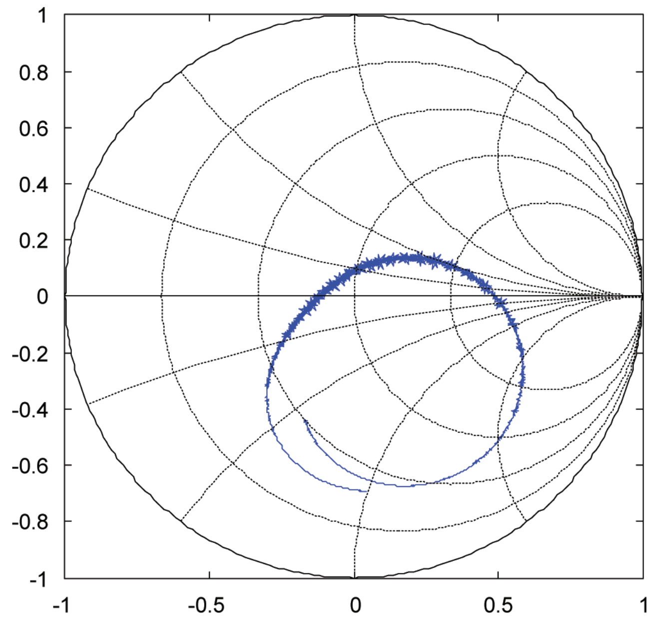


(a)

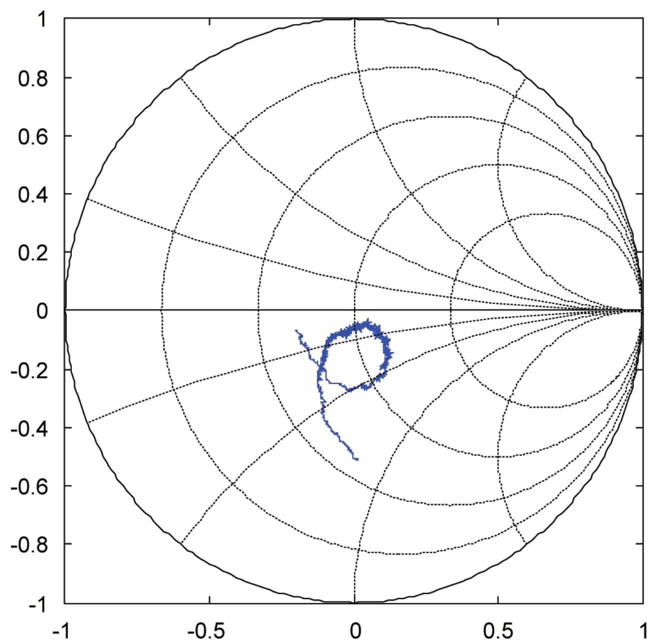


(b)

Fig. 4. (a) The device on wafer—general view. (b) The device on wafer—part of the IDT (turned 90°).



(a)



(b)

Fig. 5. A Smith chart (the axes are for the reflection coefficient) simulation (b) measured S_{11}, frequency span 5.0 to 7.0 GHz.

the possibility of using nano-imprint lithography (NIL) [7] for printing this nonvariable part of the device and then using e-beam lithography to create the remaining reflector electrodes with variable position, corresponding to the coded ID number. In this scheme, only a very small part of device will be written by the e-beam tool, which is a serial writing process. Therefore, the expected throughput of the e-beam process of only writing the coding reflector is less than 30 min per 100-mm (4-in) wafer (corresponding to 4000 ID tags).

Although the advantages of using the 6-GHz frequency range for SAW tags and, eventually, sensors may not be obvious, some aspects seem very attractive:

- Wide frequency bands are available in different countries in the 5 to 6 GHz range, resulting in the possibility of using very narrow pulses and radically decreasing the size of SAW tags. Because these frequencies are not used for mobile communications, Wi-Fi, or microwave ovens, the SAW tag interrogation systems will see less EM interference.
- If we use only 0.5 µs of delay (about 1 mm of space) for coding, with $B > 500$ MHz, we have $B \times T > 250$, which provides a proportionally large number of codes, even if we can use only part of this code capacity to avoid intersymbol interference.
- The $\lambda/4$ antenna will be only 12 mm long, so a parabolic antenna with high directivity may by hand-held. This also partly solves the collision problem—the tags can be interrogated one by one.
- We have demonstrated that despite high SAW propagation loss at 6-GHz frequencies, the smaller distance

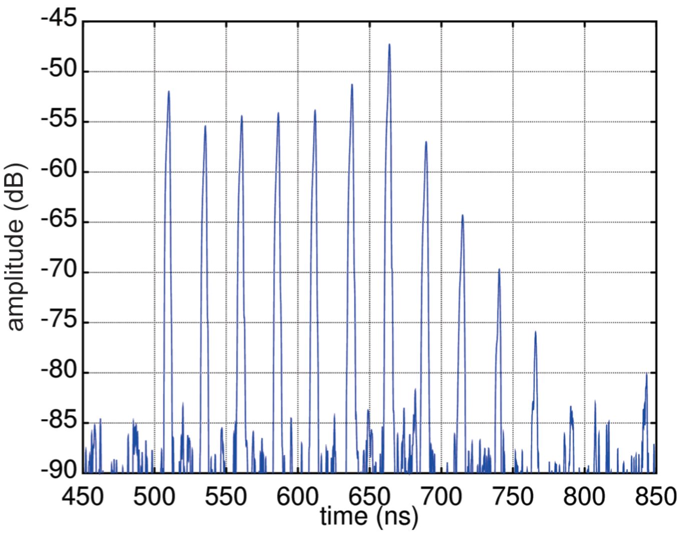


Fig. 6. Measured response in time domain, decibel scale.

results in total loss of signal in the SAW tag comparable with that for the 2.45-GHz ISM frequency band

- From a manufacturing perspective, NIL can be used for the IDT part and CAL reflectors identical in all devices and only the code reflectors (a few lines) can be written with E-beam lithography, giving a viable low-cost manufacturing method.

Available wide frequency bands are a crucial advantage for SAW tag devices, because the amount of information is proportional to the frequency band used.

Finally, this paper shows one more example confirming the ideas of K. Yamanouchi [8] that SAW devices can successfully operate up to 10 GHz frequencies.

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