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FBAR Resonators Fabricated on Insulating Substrates with Improved RF and Nonlinear Performance

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***Abstract*— This paper presents fabrication and characterization of thin-film bulk acoustic resonator (FBAR) devices on insulating dielectric materials and substrates in order to improve both linear and nonlinear performance. The fabricated devices are characterized under different temperatures and power levels and they show a clear advantage compared to conventional FBAR resonators fabricated on a silicon substrate.**

Keywords—FBAR, piezoelectric resonators, filters, substrate nonlinearity, dielectric substrates.

I. Introduction

The increasingly stringent requirements of wireless communications technology demand improved performance in miniature antenna filters that are incorporated into the RF front-ends of wireless handsets. Each new generation of filter must occupy a smaller footprint while maintaining a low insertion loss to keep transmit power consumption to a minimum. In addition, improvements in reducing the generation of 2nd order harmonic emissions and 3rd order intermodulation distortion are demanded to reduce receiver desensitization. Filters fabricated using FBAR resonator technology can be designed to perform well to these stringent requirements, but there is constant pressure from handset manufacturers to improve the filtering technology further. Because of the tiny size of the FBAR resonators comprising the filters, large strains and electric fields are produced in the constituent resonators which makes it a challenge to reduce loss and to suppress nonlinear response. This work demonstrates how insulating dielectric layers and substrates can be used to reduce both loss and nonlinear emissions in FBAR resonators, filters, and multiplexers.

We begin by demonstrating that the substrate plays a major role degrading the loss and the 3rd order intermodulation performance (IMD3) of an FBAR resonator fabricated in a conventional FBAR process. Fig. 1(a) shows the cross section of such a standalone resonator. The resonator resides on an air cavity and is anchored at its perimeter to a high resistivity (HR) silicon substrate. The resonator membrane consists of a piezoelectric layer deposited between two metal electrodes. The overlap between the top electrode, the piezoelectric layer, and the bottom electrode over the air cavity defines the active FBAR region. The FBAR resonator also includes an air bridge between the piezoelectric layer and top electrode [1].

When a high power stimulus is applied to a resonator, high electric fields, e.g. ~1e7 V/m, are induced across the AlN piezoelectric thin film independent of whether the stimulus is applied on- or off- of the resonance frequency. If and only if a stimulus is applied on or near its resonance frequency, thickness extensional mode vibrations will be excited within the resonator and hence large strains will be induced within the piezoelectric and metal films. The aforementioned high electric fields and strains, which are found within the active region will give rise to dielectric and bulk acoustic losses in the membrane, as well as nonlinear emissions due to the nonlinear characteristics of the AlN and metal films [2]. These losses and nonlinear emissions are a function of the intrinsic material properties of the thin films themselves, and cannot be mitigated without modifying the thin film material properties themselves.

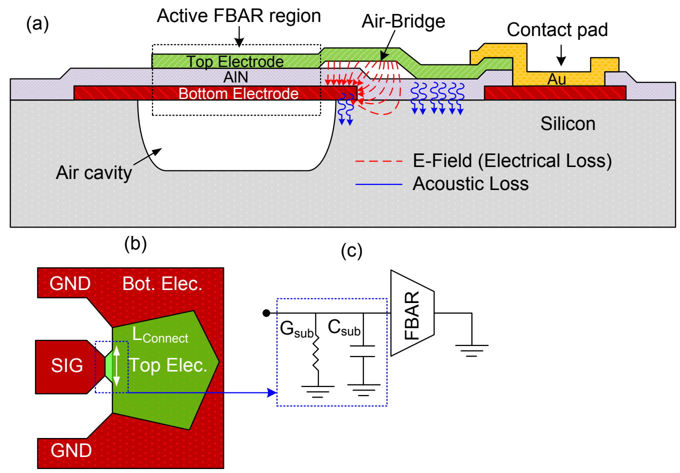

Fig. 1. FBAR resonator fabricated on HR silicon substrate.

However, as will be shown, we have identified the connect edge as being the largest contributor to loss and nonlinear emissions in a resonator. In other words, the losses and nonlinear emissions at the connect edge exceed those that are generated within the bulk materials.

With respect to loss at the connect edge, we note that high electric fields extend from the top to the bottom electrode via the air bridge, the piezoelectric layer, and the silicon substrate as shown in Fig. 1(a). The air bridge is intended to reduce the mechanical losses at the edge of a resonator by confining the lateral mode mechanical energy at the perimeter of the resonator [1]. A significant fraction of the voltage across the top/bottom electrodes is dropped across the air bridge which reduces the electric field energy that is stored in the silicon substrate. Although the use of the air bridge reduces the strength of the electric field, the electric field penetrates a few tens of micrometers deep into the silicon substrate, which, due to the high but finite resistance of the silicon substrate, induces parasitic electrical losses in the FBAR resonator. A top down illustration of the resonator, and a corresponding simplified circuit model are shown in Fig. 1(b, c). The electrical losses in the silicon substrate and the capacitance between the plates of the FBAR resonator in the inactive region are modeled using a parasitic shunt conductance and a shunt capacitance respectively. It is reasonable to assume that the value of these shunt components is proportional to the length of the connection edge.

A network analyzer was used to measure the equivalent resistance (R_p) of an FBAR resonator at its anti-resonance frequency (f_p) as a function of the length of its connection edge ($L_{Connect}$) as shown in Fig. 2(a). R_p which is a proxy for a resonator's quality factor (Q_p), degrades by more than 45% as the length of the connection edge is varied from being minimum to full length. As shown by the measurements in Fig. 2(b), the out-of-band IMD3 of the FBAR resonator also strongly depends on the length of the connect edge. For details on how out-of-band IMD3 is measured see section III. The data supports the fact that for long connection edges, the out of band IMD3 mechanism is dominated by the connection edge itself and the IMD3 emissions are almost certainly generated by the electric field that impinges upon the (electrically nonlinear) silicon underneath the connect edge. For short connection edges, the IMD3 level reaches a certain minimum residual level. This residual level is likely due to: (1) the electric field nonlinearity in the piezoelectric film itself as supported by [3] and (2) a very weak level of IMD3 generated by the silicon substrate between the bottom metal electrode of the resonator and signal or ground pads surrounding the resonator. We note that the electric field induced between pairs of bottom electrodes is much weaker than that at the connect edge as the spacing between bottom metal electrodes is roughly an order of magnitude larger. For longer connect edges, the IMD3 nonlinearities induced in the silicon underneath the connect edge exceeds the IMD3 levels generated by the aforementioned residual sources and are thus the dominant source of IMD3 emissions.

The data in Fig. 2 suggests that one can produce a resonator with the highest possible R_p value and with the minimum IMD3 response by laying it out with the narrowest possible connection edge. The problem with this technique is that a narrow connection edge will degrade a resonator's series resistance and will also limit its power handling capability. So this method of improving a resonator's performance may only be used in certain very limited situations in a filter design.

II. FBAR Resonators on Dielectric Substrates

High resistivity (HR) silicon-on-Insulator (SOI) and trap-rich substrates have been used in RF switches and BAW resonators to mitigate silicon substrate nonlinearities [4-5]. In this section we discuss various methods for how insulating dielectric materials and substrates can be used to reduce electrical losses and nonlinear generation in the silicon substrate without modifying the resonator layout [6].

Fig. 3(a) shows a cross-section of a proposed FBAR on insulator (FOI) resonator structure which employs a 3um to 5um thick interposer dielectric layer over the HR silicon substrate. The idea is to replace the top layer of the silicon substrate, which is responsible for degrading the loss and the IMD3 performance of an FBAR resonator, with a dielectric material which is both less lossy and more linear as compared with an HR silicon substrate. As the dielectric layer is made thicker, a larger fraction of the electric field energy under the connect edge will reside in the (less lossy and more linear) dielectric layer, and a smaller fraction of the energy will reside in the silicon substrate. The interposer dielectric material is also required to have a good thermal conductivity in order to extract heat generated in a resonator to maintain its power handling capability.

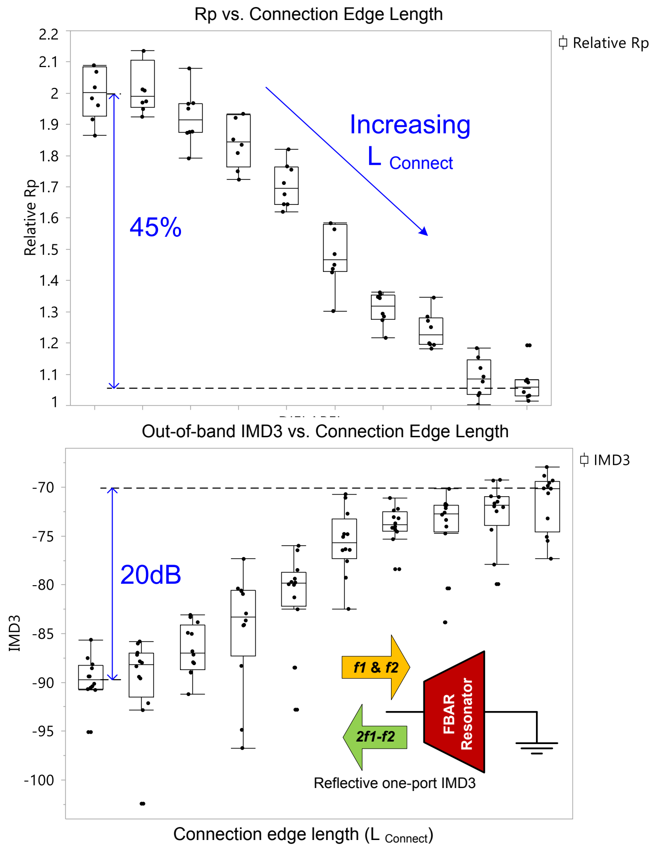

Fig. 2. a) parallel resistance (R_p) and b) 3[rd] order intermodulation product (IMD3) of FBAR resonator vs. length of connect edge.

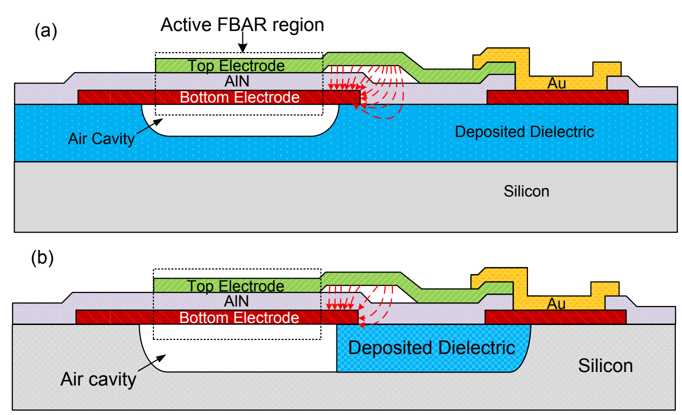

Fig. 3. Cross-section of a) FBAR on insulator (FOI) resonator and b) FBAR resonator with patterned insulating dielectric under connect edge.

In another configuration of the proposed structure, as is shown in Fig. 3(b), the silicon substrate is selectively removed under the connection edge via photo masking and is replaced by a dielectric material. This method allows a designer to selectively choose for each resonator in a filter design whether he wishes to eliminate the silicon at the connect edge in cases where he wants a resonator to have the highest possible R_p and the minimum IMD3 response, or to leave the connect edge in cases where he wishes to have a minimum thermal resistance at the connect edge for maximum power handling under high power operation.

The use of a dielectric substrate is expected to further improve the linear and nonlinear performance by completely eliminating the impact of the silicon substrate. We have successfully fabricated FBAR resonators with outstanding performance on dielectric substrates. The dielectric substrate material has a thickness of ~100um with good RF, nonlinear and thermal characteristics. We note that FBAR resonators fabricated on insulating substrates using a very different process than our own were previously reported. In that work the focus was on producing single crystal AlN films grown epitaxially on a SiC substrate [7-9]. That work, being in its early stages, reported resonator Q factors and piezoelectric coupling coefficients that were lower than that of resonators fabricated using our standard FBAR technology on HR silicon substrates. Nonlinear emission levels of the FBAR resonators on SiC was also not reported.

III. Measurement Results

FBAR resonators and filters employing the aforementioned novel processes were fabricated. Their small signal RF response, harmonic emissions and intermodulation distortion responses, and their ability to handle power was then compared.

A. Linear Characterization

The small signal S_{11} responses of 50Ω resonators fabricated on (1) standard silicon substrate, (2) 5um deposited insulating dielectric interposer layer, and (3) thick dielectric substrate are compared in Fig. 4. To aid in the comparison of the different processes, the resonators have the same resonance frequency and impedance. The resonators show similar spurious modes over a wide frequency range.

The measured Q values [10] of fabricated resonators are shown in Fig. 5. For the FBAR resonators fabricated on deposited interposer dielectric layer or dielectric substrate, the electrical losses in the silicon substrate were reduced which resulted in improved Q values. An improvement of 22% was achieved for the FBAR resonator fabricated on dielectric substrate.

B. Nonlinear Characterization

As shown in Fig. 6 a two-tone nonlinear test setup and a comb-finger device with varying gap between signal and ground was used to measure substrate nonlinearities including 2[nd] harmonic emission (H2) and 3[rd] order intermodulation distortion product (IMD3). Fig. 7 shows measured 2[nd] harmonic emission (H2) at 30°C and 70°C for different incident power levels (15dBm, 21dBm and 27dBm) and for comb layouts with a signal to gap spacing varying from 10um to 25um. As seen in this figure significant improvement was achieved using 5um deposited interposer dielectric layer over the silicon substrate or by using the dielectric substrate we were able to completely eliminate nonlinearities due to silicon substrate. Similar improvement in IMD3 was achieved as shown in Fig. 8.

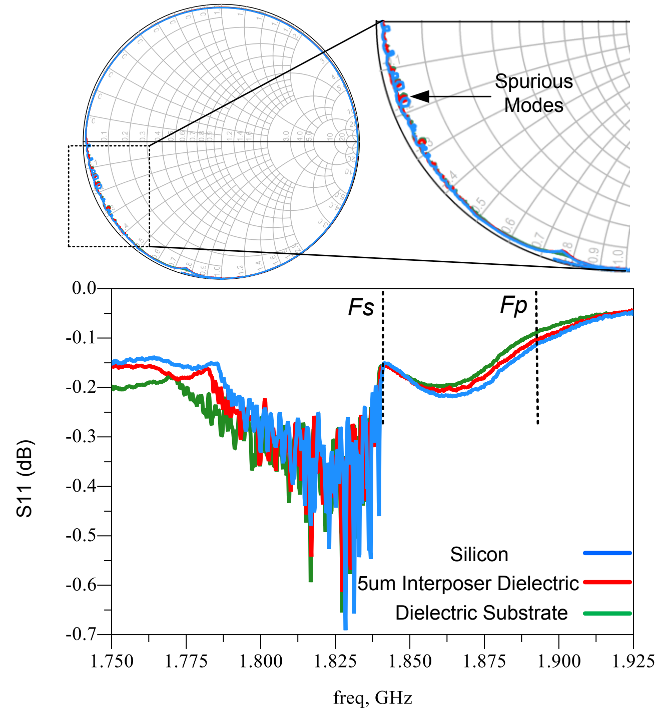

Fig. 4. Measured S-parameter response of FBAR resonators fabricated on interposer dielectric material and dielectric substrate.

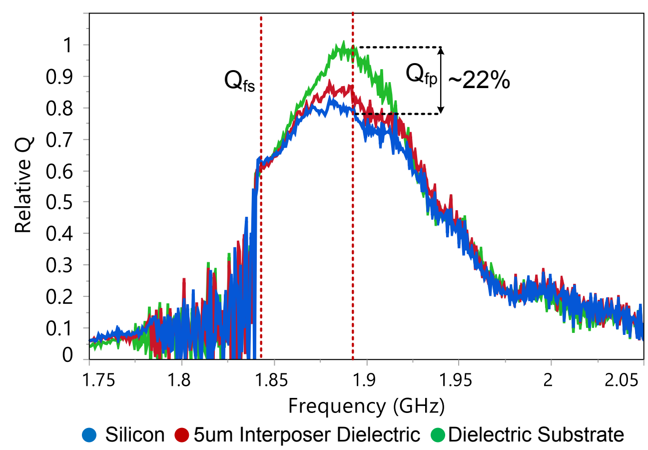

Fig. 5. Measured Q factor vs. frequency for fabricated resonators.

Measured wideband IMD3 response of an FBAR resonator is shown in Fig. 9. The reflected IMD3 tone was measured over a wide frequency range that covers both in-band and out-of-band regions. The IMD3 peak that occurs at the peak group delay frequency, is mainly limited by the intrinsic nonlinearity in the AlN piezoelectric layer. The out-of-band nonlinearity far away from resonance frequency is limited by the nonlinear contribution from the silicon substrate and it was improved by more than 30dB using the deposited interposer dielectric layer or by using the dielectric substrate.

Band-pass filters were also fabricated using conventional FBAR processing on HR silicon substrate and also using dielectric substrate. As shown in the measured wideband IMD3 response of Fig. 10, the out-of-band IMD3 level was improved by more than 20dB using dielectric substrate.

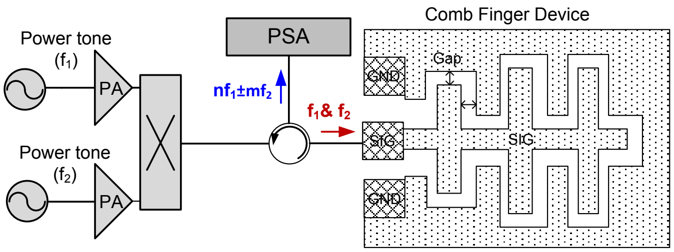

Fig. 6. Two-tone test setup to measure substrate nonlinearities using comb-finger structure.

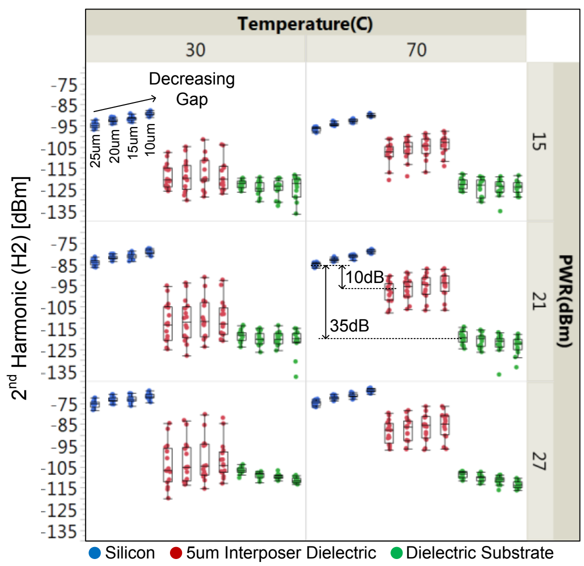

Fig. 7. 2nd harmonic emmision (H2) for comb-finger device.

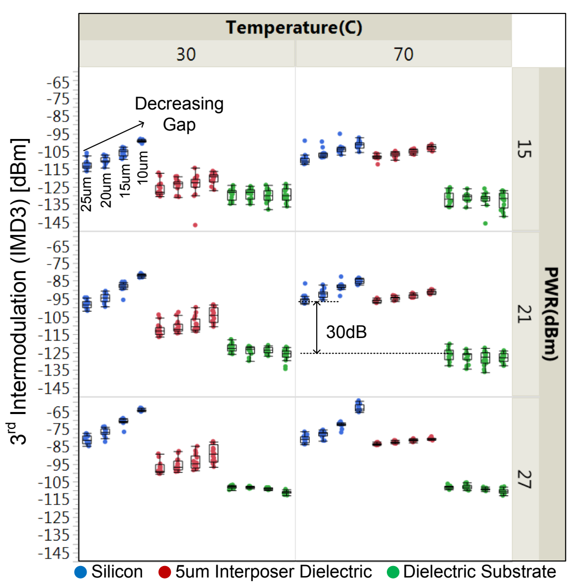

Fig. 8. 3rd order intermodulation distortion product (IMD3) for comb-finger device.

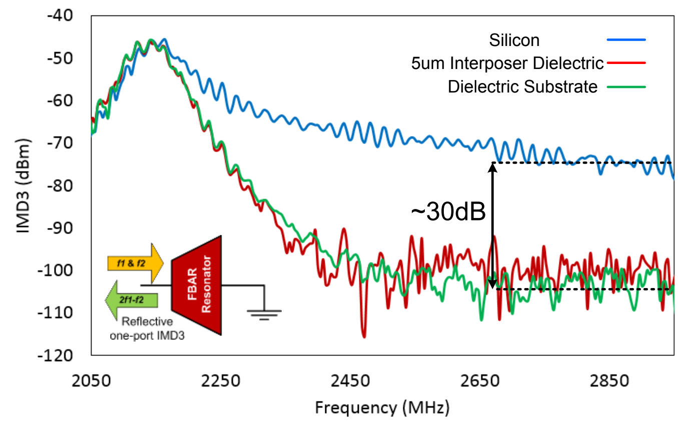

Fig. 9. Measured wideband IMD3 response of FBAR resonators.

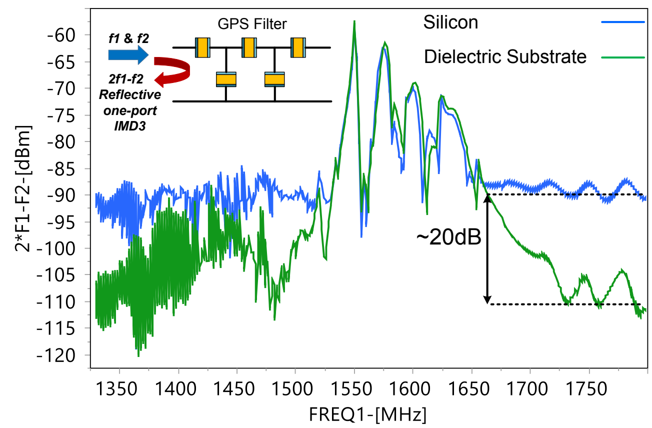

Fig. 10. Measured wideband IMD3 response of band-pass filter.

IV. POWER HANDLING

The dielectric material used to isolate the silicon substrate from strong electric fields is required to have a good thermal conductivity in order to maintain a low thermal resistance and power handling capability of the fabricated FBAR resonators and filters. Fig. 11 shows frequency shift for FBAR resonators fabricated on a dielectric material with much lower thermal conductivity compared to silicon. The resonators fabricated on dielectric substrate show 10MHz higher frequency shift compared to conventional FBAR resonators fabricated on silicon substrate. To address this issue we are using a patterned FBAR on insulator structure as shown in Fig. 3(b) where the silicon substrate is selectively replaced with dielectric material only in regions subject to strong electric field. This enables us to improve linear and nonlinear performance without adversely degrading power handling. Fig. 12 shows power handling capability of FBAR filters fabricated using different approaches proposed in this paper. A 3um to 5um interposer dielectric layer with good nonlinear characteristics but with poor thermal conductivity was used. Using the patterned dielectric approach, the substrate nonlinearity was improved without deteriorating power handling.

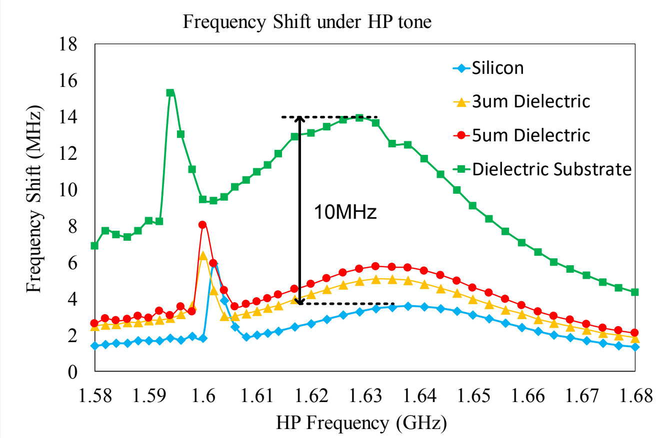

Fig. 11. Frequency shift of FBAR resonators under high power.

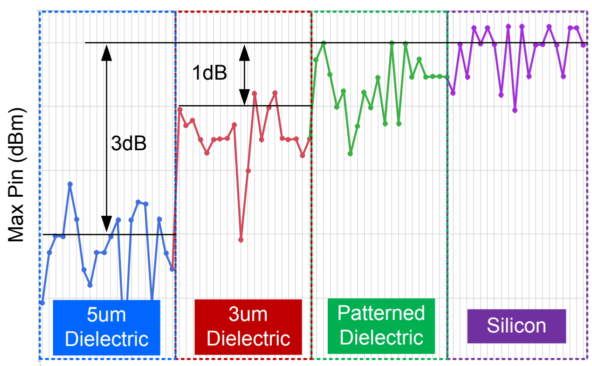

Fig. 12. Power handling perormance of FBAR filters.

V. Conclusion

We have demonstrated FBAR resonators and filters with improved linear and nonlinear performance using insulating dielectric interposer layers deposited over the silicon substrate or by using dielectric substrates. The use of insulating dielectric material prevents strong electric fields from penetrating into the silicon substrate thus reducing parasitic substrate effects. This leads to improved FBAR resonator Q and nonlinear performance. A significant improvement was achieved in the out-of-band nonlinear performance of FBAR resonators and filters over different operating temperatures and power levels. We have also addressed issues related to the power handling performance of a variety of different FBAR resonator processes.

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