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MONOLITHIC GaAs SURFACE ACOUSTIC WAVE CHEMICAL MICROSENSOR ARRAY

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ABSTRACT

A four-channel surface acoustic wave (SAW) chemical sensor array with associated RF electronics is monolithically integrated onto one GaAs IC. The sensor operates at 690 MHz from an on-chip SAW based oscillator and provides simple DC voltage outputs by using integrated phase detectors. This sensor array represents a significant advance in microsensor technology offering miniaturization, increased chemical selectivity, simplified system assembly, improved sensitivity, and inherent temperature compensation.

I. INTRODUCTION

SAW sensors are well known to offer very high surface-mass detection sensitivity for chemical sensing.[1] Achievable sensitivities are well in the sub ng/cm² range. Chemical sensing is achieved by detecting the mass loading when a desired chemical specie attaches to the selective surface coating of the sensor, thereby perturbing the SAW channel.

In addition to obvious gains in miniaturization, monolithic SAW sensor arrays offer several additional significant benefits. First, all RF signal processing is performed on-chip, which eliminates the need for RF inputs/outputs on the circuit. This allows for simplified packaging and a significant cost reduction in system assembly. Second, with all RF signals maintained on chip, power consumption is reduced and higher operating frequencies are possible for increased sensitivity. Third, integration allows for the extension to large arrays. This will enable

improved chemical identification. And finally, monolithic assembly allows for inherent temperature compensation as discussed below.

Since GaAs is both semiconducting and piezoelectric allowing for integration of RF electronics and simplified fabrication of SAW devices, it is an excellent material for monolithic sensors. The physical properties of GaAs for SAW applications are similar to ST-quartz except for a Temperature Coefficient of Delay (TCD) of approximately -51 ppm/°C at room temperature (as compared to zero for ST-cut quartz).[2] The large temperature dependence of GaAs would easily mask the desired chemical response of the microsensor unless appropriate compensation, such as used here, is employed.

II. MONOLITHIC SYSTEM

Fig. 1 shows a block diagram of the 4-channel monolithic SAW microsensor. One of the channels is incorporated into an on-chip delay-line reference oscillator ($f = 690$ MHz) that is used to drive the remaining three test channel delay lines. These channels have been coated with chemically selective sorbent polymer films. Chemical uptake on the test channels results in a mass loading on the surface of the SAW sensor, which results in a change in propagation velocity and a corresponding phase shift. The resulting phase shift is detected by homodyne mixing using special Gilbert cell mixers. Since the outputs of the gain blocks operate in high compression, it is appropriate to describe the mixers as exclusive-OR gates. Due to the two-quadrant phase detection limit of a Gilbert cell mixer, phase "dither" circuits are used to

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uniquely determine the proper phase quadrant. The phase dither circuits introduce an additional phase shift when activated, allowing for the measurement of the slope of the detected phase, which determines the appropriate quadrant.

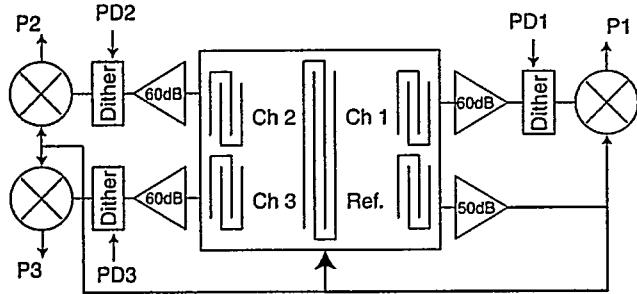


Fig. 1. Block diagram of the 4-channel monolithic SAW microsensor.

Temperature compensation is inherent to this approach. Since the SAW reference and test channels are on the same substrate and therefore at the same temperature, the phase "subtraction" process at the mixers cancels temperature dependence. This cancellation assumes that the two SAW channels are identical. In practice, the selective coatings introduced on each SAW path will unbalance the TCD's and somewhat compromise this compensation.

All signal paths in Fig. 1 are differential. A differential design is ideal for use with the symmetric inter-digitated transducers (IDT's) of the SAW delay lines and also results in very low power supply noise.

III. CIRCUITRY

The gain blocks required in Fig. 1 are realized by cascading the appropriate number of 10 dB gain differential amplifiers shown in Fig. 2. Since the goal is to measure small phase differences, and the system depends on operating the amplifiers in saturation, differential amplifiers with small phase errors at large drive signal levels were selected. This amplifier was designed to provide gain over a wide bandwidth (approx. 50 MHz to 1 GHz) to allow for research at a variety of operating frequencies. IDT dimensions

determine the operating frequency within this bandwidth; in this case $\lambda_{IDT} = 4 \mu\text{m}$, for $f \approx 690 \text{ MHz}$. The amplifier was designed for 3V operation with a nominal supply current of 2.8 mA per stage. The amplifier uses common drain output buffering to achieve a high operating frequency and to simplify amplifier cascading. The amplifier also incorporates a simple detector circuit, which allows for logarithmic power measurement by summing the detector outputs from all stages of a gain block.

The amplifiers do not use reactive impedance matching in order to maintain a small die size. The mismatch loss per IDT is approximately 10 dB. This loss was compensated by the addition of a gain stage per mismatch. This has a negligible impact on the level of integration and only adds 8.4 mW excess power dissipation per interface. The 50 dB gain block shown in Fig. 1 is followed by an additional common-drain buffer to drive the large IDT capacitance.

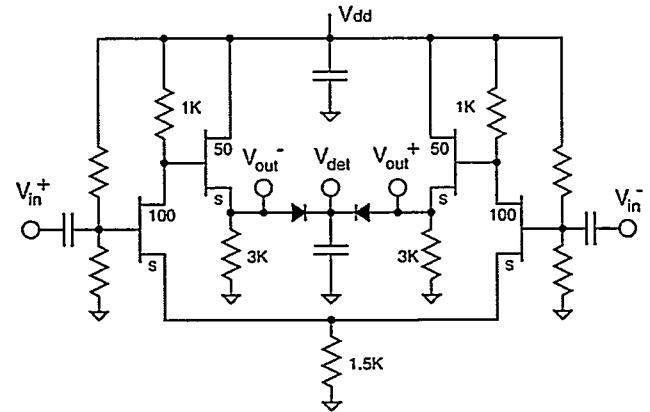


Fig. 2. Basic differential amplifier cell.

Phase comparison is performed using a Gilbert cell mixer with an integrated low-pass filter. The mixer provides good two-quadrant phase difference detection and is extended to full four-quadrant detection using the dither circuits as discussed above.

The phase dither circuits are based on a small value capacitor, which can be switched in and out of the signal path using a FET. The circuit is

designed in introduce approximately 20° phase shift when activated. The circuit is controlled by a 0 to 3V control signal and consumes no power.

IV. MONOLITHIC CIRCUIT

Fig. 3 shows a microphotograph of the monolithic 4-channel SAW microsensor. The die is 4.6 mm x 4.6 mm.

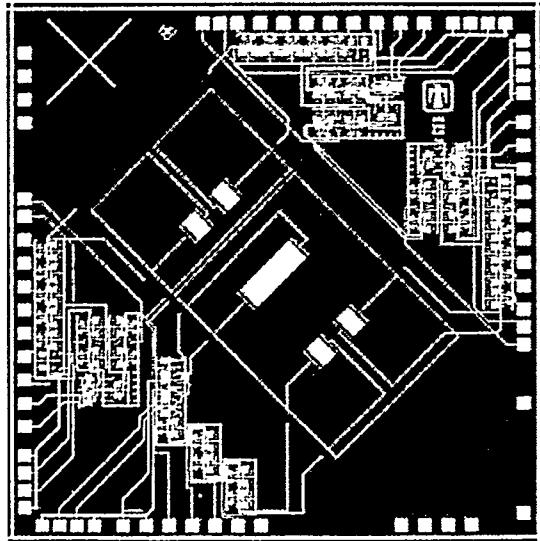


Fig. 3. Microphotograph of the GaAs monolithic 4-channel SAW microsensor array. Die size is 4.6 x 4.6 mm.

The lower-left and top-right corners of the die contain MESFET circuitry to realize the block diagram in Fig. 1. The SAW devices are located diagonally in the center of the die. The four acoustic paths are driven by one central IDT. The electronics were fabricated using TriQuint Semiconductor's TQTRx MESFET process (www.triquint.com) and the SAW devices were post-processed at Sandia. Power consumption of the circuit is approximately 266 mW (86 mW for the oscillator and 60 mW for each of the three test channel).

V. EXPERIMENTAL RESULTS

During the development of this sensor, all of the electronic blocks were fabricated and tested independently. The measured response of a four-stage gain block is shown in Fig. 4. The

amplifier was measured for phase error at high signal levels and found to exhibit only a few degrees of excess phase shift at approximately 40 dB into compression.

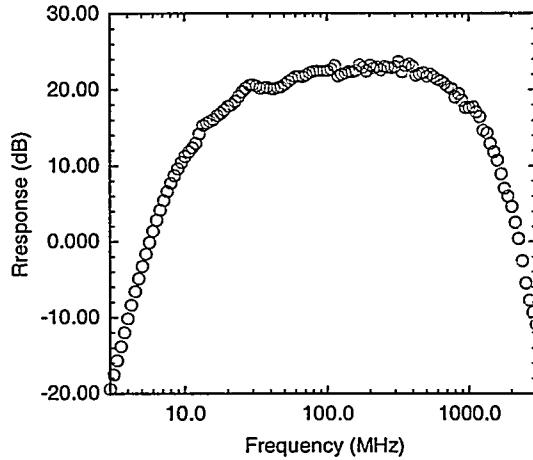


Fig. 4. Measured response of a 40 dB gain test amplifier (50Ω measurement system).

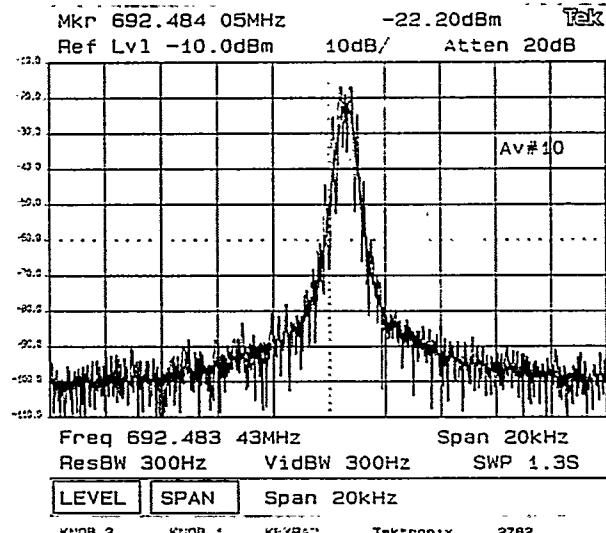


Fig. 5. Measured reference oscillator spectrum.

Fig. 5 shows a measured spectrum of the reference oscillator of a 690 MHz monolithic sensor. The oscillator is seen to have good spectral purity for this application. The operating frequency was measured as a function of temperature and found to vary at the expected $-51 \text{ ppm}^{\circ}\text{C}$. The outputs of the three phase detectors were monitored during this

temperature test and found to not measurably vary over a 30 °C range at room temperature. Thus, the circuit is functioning as designed.

Chemical detection using the monolithic sensor is on going. Fig. 6 shows a microphotograph of a hybrid 4-channel chemical microsensor using identical GaAs circuitry mounted on an ST-cut quartz substrate (see Ref. [3] for additional details). This sensor assembly is functionally identical to the block diagram shown in Fig. 1 except that the SAW array is quartz rather than GaAs. On this hybrid, three GaAs test chips surround the central SAW array. The array is covered with a transparent pyrex flow channel and has fused silica microcapillary tubes allowing for gas flow from the top and bottom.

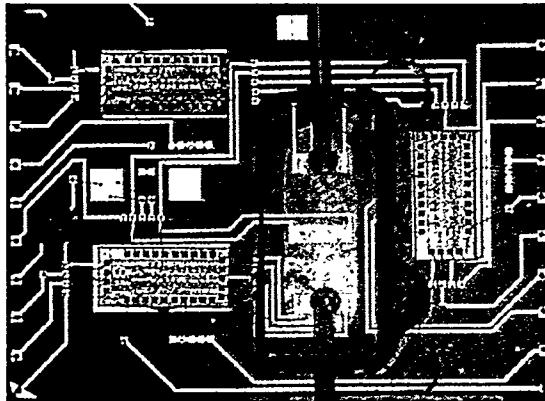


Fig. 6. Microphotograph of a hybrid (GaAs die on Quartz) 4-channel chemical microsensor array. Quartz substrate is 6.9 mm by 8.6 mm.

Fig. 7 shows the measured response of the hybrid sensor array to a 15 part per million dose of dimethyl methyl phosphonate (DMMP). The coatings (as listed in Fig. 4) have been chosen to respond with different selectivities to the test dose. Such varying selectivities are the basis for the unique detection of target chemicals. The data shown in Fig. 7 verifies operation of the sensor array.

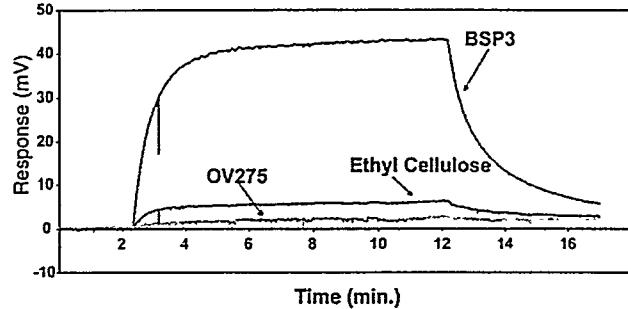


Fig. 7. Hybrid SAW array response to 15 ppm of DMMP. The three microsensor coatings were BSP3 (a hydrogen-bond acid), Ethyl cellulose, and OV-275 (a cyano modified polysiloxane).

VI. CONCLUSIONS

A low-power multi-channel monolithic SAW sensor array has been developed. This highly integrated circuit offers a significant advance in sensor technology.

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