A Review of High Frequency Ultrasound Systems

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***Abstract*— Medical ultrasound machines have been dramatically developed because of recent semiconductor development such as integrated circuit and fabrication process technology. However, proper design of ultrasound electronics are still highly desirable to be integrated with high frequency ultrasound electronic systems due to low sensitivity and high noise level caused by mismatching issues between electronic components and ultrasonic transducers. Additionally, the large parasitic capacitances and inductances of electronic components are bottleneck to design high performance ultrasound electronics. Therefore, this article which provides appropriate electronics design for high frequency ultrasound systems including integration issues with other medical imaging modalities are reviewed and discussed.**

Keywords—High frequency ultrasound electronics; Ultrasound transducers; Ultrasound systems

I. INTRODUCTION

Ultrasound systems have been widely improved for medical diagnosis for various purposes such as tumor detection, tissue characterization, intravascular imaging, ultrasonic micro-beam stimulation, cell sorting, therapeutic system, and small animal imaging [1-6]. Recently, semiconductor process technology provides the integration of the electronic components, enabling the compact ultrasound machines [7-11]. Especially, high frequency ultrasound applications provide relatively higher axial and lateral image resolution while scarifying the penetration distance of the desired tissue target compared to low frequency ultrasound applications [12-14].

To be used in ultrasound machines, the semiconductor devices need to support high voltage process technology because miniaturized ultrasonic transducer operating at high frequency operation typically has lower sensitivity and bandwidth than low frequency transducer [10, 15, 16]. The high-end performances of high frequency ultrasound machines highly depends on the ultrasound electronic systems and transducers [17].

Ultrasound machines are one of most sophisticated medical electronic systems among medical imaging/therapeutic modalities [18-22]. The performances in electronic components highly affect the system performance and configuration that also need to select proper semiconductor process [23, 24]. For integrated circuit design engineer, these consideration will be helpful to determine overall system flowchart in the ultrasound electronics design level [23, 25]. Recently, high voltage complementary metal-oxide semiconductor integrated circuit processes have been provided by several semiconductor companies such as IBM, Global Foundry, TSMC, On Semiconductor, Austria-microsystems, Hitachi, Texas Instruments, Microchip, STMicroelectronics, and Analog Devices [26]. These several semiconductor companies provide ultrasound analog transmitter electronic components such as high voltage power amplifiers, pulse generators (pulsers), multiplexers, de-multiplexers, and analog switches [27, 28]. Even though high voltage transistor devices are not required to be used for analog/digital ultrasound receiver side such as low noise amplifier, variable gain amplifier, time-gain compensation amplifier, band-pass filter, analog-to-digital converter, and digital-to-analog converter, high voltage fabrication processes still need to be used for full integration of the transmitter and receiver ultrasound electronics [26]. Nowadays, these electronic components are integrated as a single integrated circuit chip which we called system-on-chip to reduce manufacturing cost in medical markets [28].

Currently, integration with other medical imaging and therapeutic modalities like magnetic resonance imaging (MRI) guided high-intensity focused ultrasound, photo-acoustic imaging, and positron emission tomography-computed tomography (PET-CT) have been developed because these modalities have some their own advantages and disadvantages [29-33]. For example, high intensity focused ultrasound cannot obtain temperature variances inside the human beings very accurately [34]. However, MRI machines can provide very accurate temperature variance during surgery, thereby avoiding the damages of nearby healthy tissues [35].

Nowadays, these challenging issues such as high voltage semiconductor process, miniaturized ultrasonic transducer design, security issue, and integration with other medical imaging modalities are technical bottleneck to produce high performances in medical imaging markets [30, 36-39]. Next chapter introduces brief overview of the ultrasound systems, integration with other medical imaging modalities such as photoacoustic imaging and MRI. For integration with other medical imaging modalities, proper integrated circuit processes will be discussed.

II. MATERIALS AND METHODS

A. Overview of ultrasound systems

Fig. 1 shows front-end ultrasound system including array transducers to describe flow diagram of transmitting and receiving ultrasound signals [37, 40, 41].

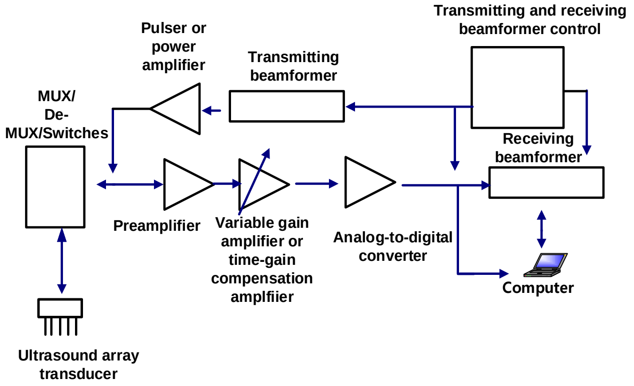

Fig. 1. Whole front-end ultrasound system.

As shown in Fig. 1, the output voltage is amplified by pulser or power amplifier that drive ultrasound array transducers through multiplexer (MUX), de-multiplexer (De-MUX), or switches [42, 43]. The MUX could reduce the channel complexity. The pulser or power amplifier can be controlled by transmitting beamformer to function the voltage amplification [44]. MUX/De-MUX/switches could block unwanted high voltage signals generated by pulsers or power amplifiers [45]. The echo signal is then, acquired by ultrasound transducer array followed by preamplifier, variable gain amplifier, time-gain compensation amplifier, analog-to-digital converter, and receiving beamformer electronics [46, 47].

Transmitting and receiving beamformer control units can provide timing duration of the transmitting beamformer and receiving beamformer electronics because pulse signals and echo signals should be operated under different time period [1]. Otherwise, the echo signals generated from ultrasound array transducers cannot be imaged in the computer [48]. Transmitting and receiving beamformer control units, transmitting beamformer, and receiving beamformer could be controlled by the computer to achieve the images from the target [1, 49].

The semiconductor process for ultrasound transceiver (transmitter/receiver) electronics are important to determine cost and performance [50]. The CMOS (complementary metal-oxide-semiconductor) and Bipolar-CMOS (Bi-CMOS) are integrated circuit semiconductor processes to be used for ultrasound electronics design. High voltage CMOS (HVCMOS) process are used to design the transmitter such as pulser or power amplifier [51].

Each integrated circuit semiconductor processes have their own advantages and disadvantages about cost, DC power consumption, flicker noise, thermal noise, gain, power, and bandwidth [52]. The CMOS process typically provides lower cost and DC power consumption compared to Bi-CMOS process [53]. HVCMOS process are higher cost than CMOS process [54].

In the analog/digital ultrasound receiver, analog-to-digital converter is one of the most expensive electronic components and it is also power-hungry electronic device in ultrasound receiver such that CMOS process is preferable due to low DC power consumption [7, 14]. However, Bi-CMOS process provides lower flicker noise and higher voltage gain capabilities than CMOS process [9]. For example, the bipolar transistor generates higher gain and lower flicker noise than Metal-Oxide Semiconductor Field Effect Transistor (MOSFET) devices under same DC bias voltages [8]. The low flicker noise is important for analog mixer circuit in the receiver for continuous wave Doppler application because the operating frequency of the Doppler signals need to be extracted to have low frequency signals [55].

The transmitter devices are one of the critical ultrasound electronic components which determine the performance of ultrasound array transducers [1, 56]. Therefore, the proper design of transmitter components could be another essential part of the whole system design. However, high voltage processes have limitation of several design issues such as relatively lower unity frequency and higher parasitic impedances in a transistor level than low voltage semiconductor processes [57]. The power amplifiers and pulse generators need to generate high power or voltage gain with low noises for array transducers producing relatively low sensitivity and these power amplifier or pulser devices directly trigger the ultrasound (ultrasonic) array transducers via the switches, MUX, or De-MUX [28].

The 0.18 and 0.35 μm BiCMOS or CMOS semiconductor processes are preferably used to fabricate ultrasound system components due to cost, dynamic range, and DC power consumption because low size semiconductor process provides low DC voltage [58]. For example, maximum DC voltages of the 0.35 μm, 0.18 μm, and 90 nm TSMC semiconductor processes are 3.3, 2.5, and 1.2 V, respectively [59-61]. Therefore, low size semiconductor process such as 90 nm TSMC semiconductor process is difficult if the circuit design is required to provide high gain for same size transistor and DC bias voltage due to large dynamic ranges of echo signals [59]. Reduced DC voltages in low size fabrication process could also limit achievement of desirable dynamic range while scarifying fabrication cost. However, DC power consumption would be reduced such that portable ultrasound machines would be better choice because they have been suffered because of battery issues.

B. Integration with photoacoustic imaging modalties

The medical ultrasound systems are integrated with other medical imaging and therapeutic modalities such as MRI, PET, CT, and optical systems to compensate their technical problems [30, 62-64]. The photoacoustic imaging which is hybrid imaging method using optical and ultrasound systems has been established due to lack of the light scattering effects [65-67]. In photoacoustic imaging system, optical systems are transmitting system to generate the light to be delivered into the target [68, 69].

The ultrasound systems are receiving systems such that the integrated circuit for ultrasound receiver would be necessary for photoacoustic imaging modalities [70]. Therefore, CMOS and Bi-CMOS process can be utilized to fabricate ultrasound receiver integrated circuit only. For ultrasound receiver electronic components, analog-to-digital converter is most power consuming electronic devices. Therefore, semiconductor process selection is dependent on the analog-to-digital converter performance. Due to high dynamic ranges of the required echo signals, 0.35 µm BiCMOS or CMOS fabrication process may be preferable to be implemented in the ultrasound machines.

C. Integration with MRI

MRI machine typically provides low spatial resolution but precise detection of the temperature variance [71]. The patients need to be monitored by suddenly increased temperature generated when high intensity focused ultrasound transducer devices are used to eliminate cancer tissues [36]. Accordingly, MRI guided high intensity focused ultrasound machines use cancer therapy under high temperature situation to avoid healthy tissues except the cancer tissues [35, 71]. Therefore, HVCMOS semiconductor process should be used to design high gain and low noise power amplifiers or pulse generators which need to trigger high intensity focused ultrasound transducers typically operating less than 2 MHz frequency because HVCMOS process could provide high power gain for limited frequency ranges for current semiconductor process [9].

Additionally, high intensity focused ultrasound transducers need to generate highly constant acoustic powers for longer time period than diagnostic ultrasound machines such that integrated circuit design for power amplifiers or pulse generators are required to produce constant power gains for long time period [35, 72]. These integrated circuit performance is quite difficult to be achieved because HVCMOS process generates high parasitic capacitances for large size MOSFET devices which reduce the bandwidths [51, 52, 73].

The MRI guided focused ultrasound system was provided by UCLA obstetrics and gynecology department [74]. This system uses high intensity focused acoustic waves to treat the fibroids of the tissue [74]. First, medical doctor obtain the fibroids on MRI images from the pelvic region of the patient and then, ultrasound waves heat desired sport in the uterine fibroid to 85^{o}C temperature and this process is repeated around several hundred times until the cancer cells are removed [27, 75].

III. CONCLUSION

This review article covers how proper semiconductor process needs to be selected for high frequency ultrasound integrated circuit electronics depending on system level and imaging/therapeutic applications. For integrated circuit semiconductor process, there are performance trade-off when designing high frequency ultrasound electronic components between Bi-CMOS, CMOS, and HVCMOS processes. Under same DC bias voltage level, the Bi-CMOS process can provide lower flicker noise level and higher transistor gain than CMOS process such that ultrasound receivers like variable gain amplifier, time-gain compensation amplifier, and analog-to-digital converter could be preferable. CMOS process can provide lower power consumption and fabrication cost than Bi-CMOS process such that ultrasound receiver component is desirable to reduce power consumption for portable ultrasound machine because portable ultrasound machine can be suffered by limited battery. HVCMOS process need to be used for ultrasound transmitters because of high voltage capability.

Nowadays, there are hybrid imaging modalities because each medical imaging modality has its own advantages and disadvantages such as penetration depth, sensitivity, and image resolution. To overcome these technical issues, hybrid imaging modalities are proposed for diagnosis and treatment of the patient disease. In photoacoustic system, ultrasound receiver could be integrated. Therefore, Bi-CMOS process or CMOS process could be used depending on the characteristics such as portability, image resolution, and sensitivity.

For MRI guided high intensity focused ultrasound applications, high voltage ultrasound transmitters such as power amplifiers or pulse generators are used such that high voltage CMOS process need to be utilized to provide high voltage power gain of pulse generator or power amplifiers. Therefore, integration between different modalities need to be considered due to performance optimization, application needs, system configuration, portability, image resolution, and sensitivity.

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