Journal of Electrical and Electronic Engineering
2022; 10(5): 199-206
http://www.sciencepublishinggroup.com/j/jeee
doi: 10.11648/j.jeee.20221005.13
ISSN: 2329-1613 (Print); ISSN: 2329-1605 (Online)

Sensor Analysis and Semiconductor Process Advances for Autonomous Vehicles

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To cite this article:
Jorge Vargas, Antonio Saavedra. Sensor Analysis and Semiconductor Process Advances for Autonomous Vehicles. *Journal of Electrical and Electronic Engineering*. Vol. 10, No. 5, 2022, pp. 199-206. doi: 10.11648/j.jeee.20221005.13

Received: August 24, 2022; **Accepted**: September 9, 2022; **Published**: October 11, 2022

Abstract: The future of the automotive industry is highly dependent on the integration of electronics into vehicles, particularly as the deployment of advanced electric vehicles (EVs) with varying levels of autonomy have come to fruition. On-board sensors in today's automobiles, such as cameras, radars, lidars, and ultrasonic radars, provide detection and uniformity scenarios in various environments and weather conditions. New technologies have also been deployed, such as 3-D vision and global navigation satellite systems (GNSS). In addition, 5G networks are impacting the development of connected and autonomous vehicles (AVs) making them safer and smarter. The use of on-board sensors in vehicles requires testing, verification, and validation, in order to provide safety, stability, reliability, and precision. Integration of these various systems and networks will aid in the creation of the vehicle-to-everything (V2X) environment. Silicon based integrated circuit (IC) architecture, such as SiGe CMOS and BiCMOS have enabled scaling and cost reduction of advanced sensors. The semiconductor's value stack of multiple IC architectures, cost advantages, reliability, and sensor fusion can be combined with 5G/mmWave networks for Silicon and Gallium Nitride (GaN) technologies. Advanced materials will also play a pivotal role in driving the further scaling of sensors. These approaches currently play a key role in the process and manufacture of CMOS and MOSFETS. In this paper, an analysis of the current state of advanced sensors is presented, along with semiconductor process advances for AVs. IC innovations such as system integration, sensor local systems, and sensor health are also covered.

Keywords: Autonomous Vehicle (AV), Camera, Lidar, Radar, BiCMOS, SWIR, SiGe, GaN

1. Introduction

Radars have become more cost-effective and reliable since the automobile industry began proliferating sensors in the 1980s. A large percentage of automobiles in 2022 will be operated by on-board sensors such as cameras, radars, lidars, and ultrasonic radars, offering realistic scenarios for detection and consistency in a variety of environments. Each class of sensors has advantages and disadvantages, such as range between objects, object identification, elevation and azimuth angles, and weather susceptibility [1]. The semiconductor process technology has been a driving force for the reduction in cost and increase reliability of these sensors. Efforts have been made to develop low phase noise oscillators and high-power amplifiers with low breakdown voltage transistors. These challenges, however, have been overcome by new digital architecture designs and chip stack hardware. In addition, they can outperform more "RF friendly" technologies such as Silicon Germanium & Bipolar Complementary Metal-Oxide Semiconductor (SiGe BiCMOS) over the entire operating range. Advanced complementary metal-oxide semiconductor (CMOS) processes can carry out digital signal processing (DSP) functions as they will perform actions on analog signals using algorithms. In this paper, we will present sensors background, advanced process technologies on AV system designs and requirements for testing and verification. The current state of IC semiconductors, in-flight innovations, and advantages of 5G network semiconductor technologies for automated vehicles will be presented.

2. Sensor Background

2.1. Radar

Radar originally operated at 24, 74, 77, and 79 GHz which were separated out to work for short-range radar (SRR), medium-range radar (MRR), and long-range radar (LRR) [2]. In July 2017, the Federal Communications Commission (FCC) adopted to expand the spectrum for automotive radar sensors. The agency is phasing out 24 GHz and opening frequencies in the 77 GHz range for automotive use, part of the 76-81 GHz short-range band with millimeter wavelengths (mmWave). Having to provide higher resolutions in this range, radars experience a reduction in antenna area and less interference with other on-board devices.

Therefore, novel IC semiconductor techniques are necessary in the transceiver designs to enable the system to achieve a high range resolution and to detect objects at a close range. One major hurdle for terahertz transceivers in CMOS is the limited high-frequency performance of transistors [3]. For signal generation above 200 GHz, heavily driven nonlinear circuits with harmonic output are a promising solution. However, it is yet to be determined whether CMOS technology can catch up with their millimeter-wave counterparts in the near future. Since SRR has the capability for parking assistance and other close proximity applications, it may be used instead of ultrasonic sensors [4]. Texas Instruments has been using frequency-modulated continuous waveform (FMCW) and phase-locked loop (PLL) technology where distance and velocity can be detected by the radar, resulting in a more accurate signal than traditional use of mmWave sensors. Analog Devices deploys chips with a high-power supply, providing higher bandwidth than competition, and uses two detectors to analyze traffic signals, a viable in-use application. Highly integrated, high frequency circuit designs in advanced silicon technologies are underway. A 24-Ghz SRR transceiver has been reported in a SiGe process with limited integration and bandwidth, and high-power consumption. Experimental results on a 75 - 110 GHz W-band transceiver in 90-nm CMOS have also been reported by industry. SiGe will be aligned with the requirements for AV testing and verification. Meta Materials Inc. has developed a proprietary highly transparent Nanoweb® material, fabricated as a metal mesh, to improve radar absorption and reflection. It boasts a wide range of frequencies from 400 MHz – 92 GHz, with surface area coverage of as much as 300 mm [5].

The dSPACE Automotive Radar Test System (DARTS) has versatile features for testing radar systems. These will help quantify the quality and reliability developed by industry for incorporation into consumer AVs. For high-frequency systems, operating in the GHz range, which are used for safety-critical applications, reliability, precision, and stability of the functions are particularly important. This is exactly what DARTS offers by means of high-quality components and sophisticated RF circuit technology. The DARTS product family’s dedicated design offers a low minimum distance (0.6 m) and also enables the simulation of large distance echoes (up to 1,000 m). DARTS is regarded as the radar test system with the smallest RF front ends in the world and is therefore ideally suited for dynamic angle simulations. The small size and low mass of the RF frontends offer almost unlimited possibilities in terms of test setups. Furthermore, 77-Ghz long-range radars and 77-81 GHz short-range radars Si technologies are under development and novel circuit techniques employed in the transceiver designs will enable the system to achieve a high range resolution and to detect objects at a close range [6-8]. It is a suitable application for SRR systems and for the AV requirements on testing and verification.

2.2. Lidar

The generation of 3D environment maps is being implemented by industry as part of the object scanning processes. Lidars rely on two wavelengths: 905 nm and 1550 nm, which results from atmospheric transmission windows and availability of high-power pulsed sources. [9] During the initial stages of AVs development, 905 nm pulsed lidar systems were chosen due to their availability. However, these systems had serious limitations such as prohibitive cost, inefficient mechanical scanning, interference from other light sources, and eye-safety power restrictions that limit their detection range to approximately 100 m. This prompted the shift to the retinal-safe 1550 nm band because water in the atmosphere begins to absorb energy at 1400 nm, thus allowing higher pulse powers ranging from 200 to 300 m [9]. Lidars used for vehicles belong to Class-1 and are safe under all conditions of normal use [10].

Luminar reports specifications on lidars including 500 m maximum range and less than 10% reflectivity at 250 m (about 820.21 ft). Accordingly, these lidars have the potential to be the most efficient, and low-cost, if all expectations are met. Analog Devices (AD) offers powerful radar sensors with higher frequencies than competitors and use two detectors to analyze traffic lights. Since their products already have practical uses, they seem quite reliable.

For scanning lidars, the platform emits pulses from a set of diodes mounted on a rotating pod or using a rotating multi-faceted mirror. The moving parts in these designs, rotating at 300-900 rpm, represent points of higher failure rate in rough driving environments. Other approaches that can reduce the need for mechanical steering are to use a microelectromechanical systems (MEMS) mirror to steer the lens electrically or use optical phased array (OPA) technology. On the other hand, flash lidars flood the scene within the field of view (FOV) of the detector with light. The detector is an array of avalanche photo diodes (APDs), where each independently measures time of flight (ToF) to the target feature imaged on that APD has not released a 100% fully functioning solid device yet. Ideally, a phased array lidar would be quite versatile and cheap, but this technology has yet to function. Current work in the automotive sector is constructing a typical mechanical steering lidar. For scanning LiDARs, the platform emits pulses from a set of diodes mounted on a rotating pod or from a rotating multi-faceted mirror. The moving parts in these designs, which rotate at 300–900 rpm, represent points of high failure rate in harsh driving environments. Other approaches that can reduce the need for mechanical steering include using a microelectromechanical systems (MEMS) mirror to steer the lens electrically or using optical phased array (OPA) technology [11].

2.3. Vision Systems

Self-driving vehicles can rely heavily on cameras to perceive the surrounding environment. According to the electromagnetic spectrum, most cameras can be classified as visible (VIS) or infrared (IR). VIS are mostly used due to their low cost, high resolution, and their capability to differentiate between colors. Connecting two VIS cameras with a predetermined focal distance allows stereo vision to be performed, and hence, a 3D representation of the scene around the vehicle. However, even in a stereoscopic vision camera system, the estimated depth accuracies are lower than the ones obtained from active range finders like radars and lidars.

An analysis of object distinction, by delineating the concerns of the camera's interpretation of traffic lights, has been studied [12]. Due to image saturation, the correct light may not be perceived by the sensor. Additionally, due to the integration of LEDs into traffic lights, coupled with higher speed cameras, the concern of detecting a blank traffic light has arisen. A method of continual object tracking, while considering the originator of the detected light, was proposed to allay these concerns. This method of object distinction is more effective than existing methods. However, the demand for computational 3D map cameras with low resolution has increased, where lighting and weather conditions may interfere with the imaging process. Infrared (IR) cameras use infrared wavelengths ranging from 780 nm to 1 mm. For certain applications, they can be extended to near-infrared (NIR: 780 nm–3 mm) and mid-infrared (MIR: 3–50 mm; known as thermal cameras). [11] IR cameras are less susceptible to weather and lighting conditions, and they can compensate for some of the shortcomings of VIS cameras in situations where there are peaks of illumination (e.g., at the exit of a tunnel). They can also be used to detect warm bodies, such as pedestrians and animals. [11]

2.4. Global Navigation Satellite System (GNSS)

Vehicle-to-everything (V2X) is a system that encompasses both vehicle-to-infrastructure and vehicle-to-vehicle systems. Originally, this system was set to the 5.9 GHz band, but due to multiple parties accessing the band by different means, accessibility within the band diminished. It is suggested that shifting the frequency band will mitigate this issue [13]. The concerns that arise are greater frequencies causing the wave to have a more optical-like behavior. On the other hand, increasing the wavelength would reduce the piercing capabilities of the wave. For stability, the transmitter and receiver must be within line-of-sight of each other. If not, more power is required to account for the multipath trajectory between the two. The proposed frequency band shift is 3.4-3.8 GHz. Even though these frequencies have high attenuation rates and power concerns, excessive distances are not needed for this system to function effectively. Alternatively, GNSS is a blanket system which encompasses Global Positioning System (GPS) which is the most commonly used navigation system for AVs [14, 15]. GNSS utilizes most of the L-Band and some of the S-Band frequencies, 1-2 GHz and 2-4 GHz, respectively. This range of frequencies is located within an ideal spot for atmospheric transmissions. V2X comes into play when using 5G mmWave networks using either silicon or GaN technologies. This technology's low latency makes AVs extraordinarily safe and reliable on the roads—safer than vehicles today that are operated by people.

3. Advanced Process Technologies

3.1. Innovative Materials for Current Technology

According to Electronic Sensing Technologies for AGVs, a general trend is to combine two sensors into one device, often a camera with either lidar or radar (system integration). Silicon (SiGe: CMOS, BiCMOS) fabrication technology has the potential to reduce sensor development cost to an extent that will make automotive sensor technology economically viable. Figure 1 shows TRX patch antennas with high isolation are being considered as the next generation of radar sensors in automotive sensor-fusion systems. Also, S. M. Patole's system model embraces the automobile radar systems through applying imaging algorithms [16]. For object recognition and classification, fusing multiple radar sensor information into a perception process is essential [17]. Unifying perception of 3D environmental maps and image data, a representation of the area of interest can be generated using object generation to realize semantic grouping for charge coupled device and lidar sensors.

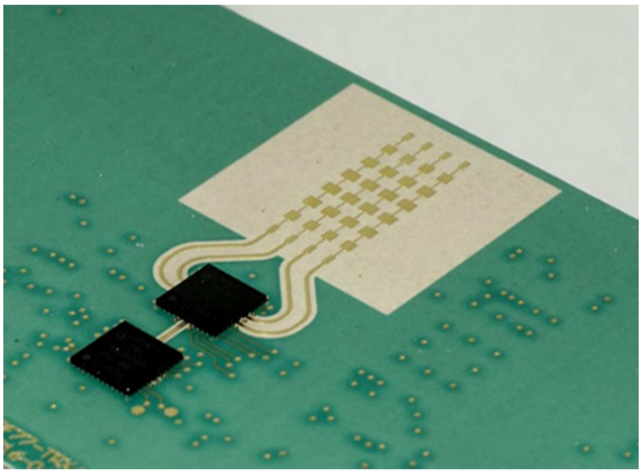

Figure 1. *Next Generation Radar Sensors in Automotive Sensor Fusion Systems (TRX patch antennas with high isolation).*

The decision-making on autonomous vehicles relies on recent advances, including how the vehicles decide where to go, how vehicles use the data provided by their sensors, how the interaction with other vehicles affect, and how to ensure that the vehicle control and systems are safe and running. The recent advances respond to a variety of uncertainties and questions as transportation becomes a utility and education refers to autonomy.

Whereas ON Semiconductor's image sensor (RGB-IR) uses NIR (near infrared) technology, TriEye went a step further by showing off a SWIR (short wave-based infrared) camera as seen in figure 2, which a) represents the receiver and transmitter architecture, b) the antenna array diagram, c) the flow chart, and d) the normalized power vs angle simulation. SWIR's benefits include its ability to see objects under any weather/lighting conditions [18]. More important, SWIR can also identify a road hazard, such as black ice, in advance, since SWIR can detect a unique spectral response defined by the chemical and physical characteristics of each material. TriEye reports it has discovered how to design SWIR by using CMOS process technology. For object recognition and classification, fusing multiple radar sensors information into a perception process is essential.

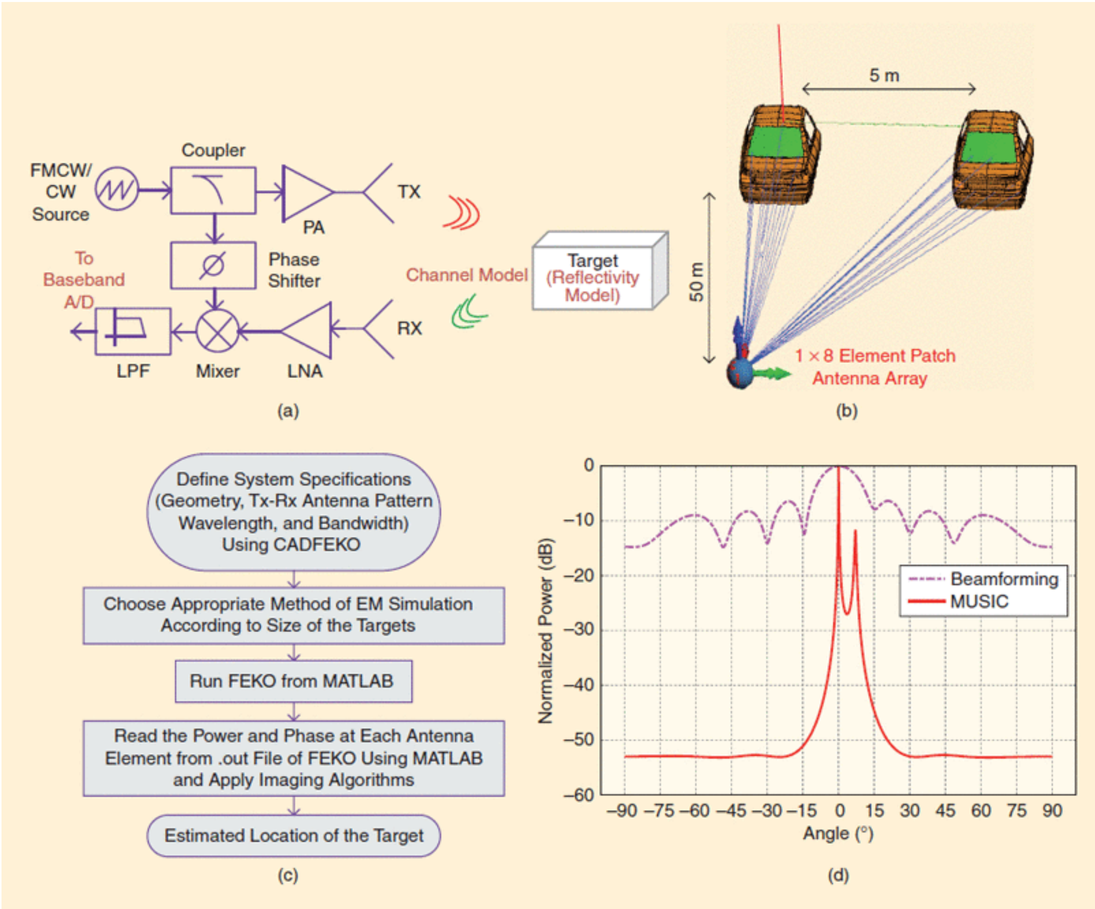

Figure 2. *S. M. Patole's system model.*

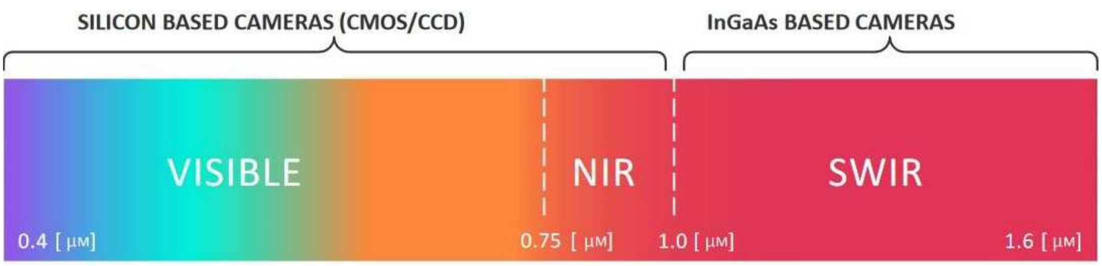

Figure 3. *Portion of electromagnetic spectrum from visible to SWIR wavelengths.*

The current state of transistor modeling and packaging is shown in figure 3. This is the reportedly achieved frequency operation of THz circuits including SiGe, InP, CMOS, and GaAs technologies. The current states of GaN and CMOS technology show similar frequency spectra, with GaN requiring a higher wafer cost, while its mask cost is far less than cutting-edge CMOS [19]. Finding a way to design SWIR using CMOS process technology is advantageous due to the low cost of making these ICs. Therefore, THz circuits will be appropriate for AV testing and verification purposes due to a flexible frequency spectrum.

Table 1. *Current outling BICMOS Technology.*

Parameter	Units	0.18um BiCMOS Gen 1	0.18um BiCMOS Gen 2	90nm BiCMOS
SiGe fMAX	GHz	270	320	400
SiGe BVCVO	V	6.1	5.2	5.2/7.0
MOS	V	1.8	1.8	1.2
I/O MOS	V	3.3	3.3	3.3
TL Loss	db/mm	1.5	0.9	0.85
Cu metal layers	-	5	6	7
TFR Rsh	Ω/sq	50	50	45
MIM Cap	fT/um^2	1.6	1.6	2.0
Metal Fuse	-	Yes	Yes	Yes
Varactor TR	F/F	2.2-2.7	2.2-2.7	2.2-2.7
Varactor Q	-	4.5-8	4.5-8	4.5-8

While SiGe bipolar and SiGe BiCMOS (Table 1) processes are currently leading, a 79 GHz single chip radar CMOS is currently under development. One reason CMOS is under development is because it allows higher integration (in-sensor processing) and will come at a lower cost [17]. The downside is that CMOS is a very advanced circuit design, so it will likely exist alongside the BiCMOS. Experimental results on a 75~110 GHz W- band transceiver using 90-nm CMOS have been reported by industry. CMOS may seem advantageous, but it has tradeoffs [20]. Notable tradeoffs include lower power output while also consuming less power. At the same technology node, it is more expensive than BiCMOS but has a higher digital gate density output. The following items are examples of the in-sensor processing integration and local systems such as smart cities and ecosystem on the automotive industry.

Below are some of the 5G revolution developments of smart cities:

1) It will boost the current technology giants as internet search, social media and e-commerce become more ingrained in our daily lives.
2) Artificial intelligence applications and virtual reality devices will proliferate in this environment and will require advanced chips to power innovation.
3) Devices will be able to “talk” to each other instantaneously.
4) Connectivity between vehicles and infrastructures will gather vital information, and thereby, reduce traffic congestion and increase road safety.
5) Leading semiconductor companies, such as Intel and Qualcomm, are advancing toward an ASICs revolution, combining large available bandwidth at 5G frequencies with new innovative digital radio and antenna architectures. These companies are creating chips to turn autonomous vehicles into mobile data centers, allowing driverless cars to make real-time, complex decisions.

Ecosystem items transforming the automotive industry:

1) From the adoption perspective of this ecosystem, 2025 is seen as the target timeframe by which time we will start seeing autonomous cars on our roads.
2) On the radio technology side, technologies with low latency, such as DSRC and 5G, used for communication between the cars themselves and between the cars and infrastructure, were identified as the most suitable and promising given the critical safety applications communication in this industry. 5G is seen as the main technology given that adoption of 5G coincides well with the adoption of autonomous vehicles.
3) A group of researchers are investigating how to run machine learning algorithms on the tiniest microprocessor out there. Machine learning at the edge will drive better privacy practices, lower energy consumption, and build novel applications in future generations of devices e.g., BiCMOS 90 nm technology, which is suitable for AV testing and verification requirements. Many companies are currently focused on building specialized silicon for machine learning in order to train networks inside data centers. They also prefer silicon for conducting inference at the edge. That is, running data against a machine learning model to see if data matches the model’s results.
4) Some key requirements of semiconductor technologies for ADAS and AV are a combination of high Fourier transform (Ft) for high-speed analog and mm-wave circuits and the capability to carry out substantial amounts of digital signal processing. This calls for automotive qualified, deep submicron CMOS technologies and 28nm seems to be the optimum node currently for RF performance and DSP integration. The breakthroughs in analog and mm-wave performance made with the new circuit architectures on CMOS have made it possible to integrate these functions with the substantial amount of digital signal processing required by ADAS and AV systems.

Fast growing amount of data, low-power edge computing for artificial intelligence and high-performance computing are some of the real-world tendencies for self-driving vehicles. Their physical environment is mapped or can be updated rapidly in real-time. Edge-adjustable multipath infrastructure can collect massive amounts of raw and sensitive data. Since 5G networks have lower latency and can unload computing tasks, this will allow for faster responses. Artificial intelligence (AI) algorithms are used to provide a large number of images and video by detecting and correcting flaws. They can also help to reduce human fatigue errors. It is essential to collect data from various sensors, build an AI software, and handle the network engineering that connects those sensors to the software. All algorithms must comply with privacy issues before being deployed to customers in order to release data for security networking purposes.

3.2. Innovative Materials for Future Technology Challenges

3.2.1. Gallium Nitrite (GaN)

GaN is capable of handling a much higher voltage in a small area at the chip level, and it powers a wider range of mmWave frequencies than standard silicon as shown in figure 4. Most chipmakers responded by assuming they would be supporting both materials, with some focusing more on one than the other. Wolfspeed, NXP, Sumitomo, and other chipmakers, especially those with experience in the microwave communications market, have promoted GaN for years as a likely successor to LDMOS in 5G base station power amplifiers (PA) and other applications. With the big boxes, however, the issue is how much power is wasted, not only how much is used, according to Earl Lum, president of EJL Wireless Research. “Those power amplifiers are only maybe 30% or 35% efficient, so if you put 100 watts into it, you only get to transmit maybe 35 and the other 65 turns into heat.”

“GaN works fine on isolated uses and a few high-energy applications where it is already popular — lidar and radar in particular,” according to Alastair Upton, Anokiwave’s chief strategy officer. Good designers can get silicon to do astonishing things, but a large amplifier will dissipate heat more slowly than a small one. So, GaN or anything else that can handle the same voltage as silicon in a much smaller space makes the whole process more power-efficient, said Alex Lidow, co-founder and CEO of GaN power-supply provider Efficient Power Conversion (EPC).

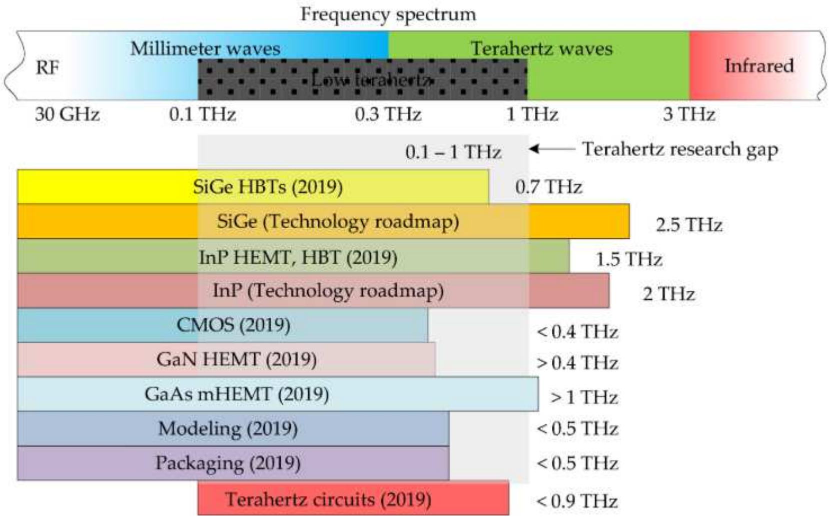

Figure 4. *Frequency spectrum operation of THz circuits. Source: Bozanic & Sinha.*

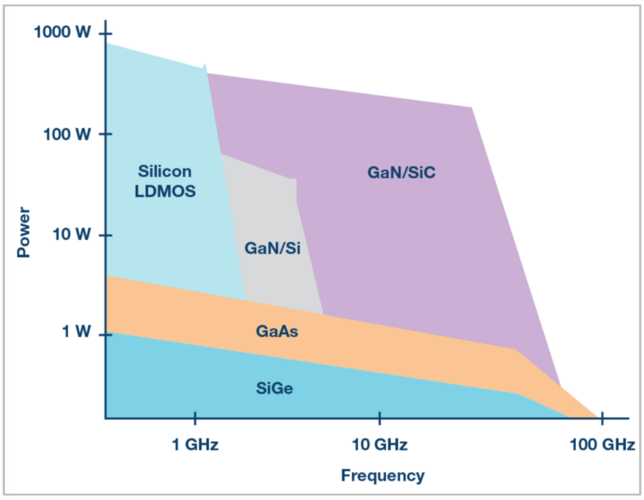

Figure 5. *Comparing power and frequency of different materials in the microwave range, which includes mmWaves. Source: Analog Devices.*

3.2.2. Silicon Carbide (SiC)

Although possessing lower mobility and electric field strength than GaN, SiC has a large advantage in thermal conductivity. This, along with its low intrinsic carrier concentration, allows it to be potentially used in extreme operating environments, such as planetary exploration. Traditionally, one of the major drawbacks of SiC was the inability to fabricate sizable substrates, but this is no longer the case with wafer diameters of 200 mm being achieved [21].

3.2.3. Gallium Oxide (Ga_2O_3)

Gallium oxide is another material that shows promise for radar and 5G wireless RF power applications. Some of the reasons for optimism are that Ga_2O_3 possesses a much greater critical electric field strength and wider band gap than GaN. Unlike most oxides, gallium oxide’s electrical conductivity can be tailored using doping techniques common in semiconductor processing, such as ion implantation and epitaxy. Bulk substrates have also been produced using the Czochralski method, which is another problem with most wide band gap semiconductors. The greatest material property challenge facing gallium oxide is its low thermal conductivity, which limits its ability to dissipate heat efficiently [22].

4. Conclusion

Radar and lidar systems base their operation on measuring the time it takes a pulse of light emitted from a laser diode, in infrared and near-infrared ranges, to reach the system’s receiver. The use of short-wave-based infrared (SWIR) cameras, while promising, has been limited to military, science, and aerospace applications, due to the extremely high wafer cost of indium gallium arsenide (In GaAs) used to build it. For example, a beam steering lidar having rotating mirrors requires a high manufacturing cost and skilled labor. According to IEEE Processing Magazine "Silicon semiconductor technologies have had a profound impact on the design of automotive radar systems" [16]. It then details multiple algorithm implementations (models), of which is shown previously. A general trend is to combine two sensors into one device, often a camera with either lidar or radar (system integration) Silicon (CMOS, SiGe and BiCMOS) fabrication technology has a potential to reduce sensor development cost to an extent that will make automotive sensor technology economically viable. Studies on these more expansive dialogues would then contribute to the overall sensor information in AVs.

The trend of the automotive arena is incrementally in need of electronics in vehicles, which continues to accelerate with the adoption of electrical vehicles (EVs) and ADAS. As vehicles increasingly become more technological, the need for increased semiconductor presence in the market continues to rise. This trend is towards the fusion of different sensors starting from ultrasonic radar and front camera to a short-range radar, driver camera and lidar to the full implementation of SENSOR fusion. After implementation, the requirements for testing and validation for AVs will be suitable and adequate. By continuously monitoring sensor data and providing early warnings, sensor health reduces downtime. This will save money on product recalls and scrap products.

Acknowledgements

The research contained here was supported by MTSU.

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