# WIDE DYNAMIC RANGE RF MIXERS USING WIDE-BANDGAP SEMICONDUCTORS

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## ABSTRACT

This paper describes how wide-bandgap semiconductors, such as silicon carbide or gallium nitride, can be useful in developing a wide dynamic range rf mixer with low intermodulation distortion products, instead of using conventional narrow bandgap semiconductors, such as silicon and gallium arsenide junctions, which have limited dynamic range. A wider dynamic range mixer allows for the reception of weak rf signals, even in the presence of strong undesired signals. This feature also permits closer location of rf sources and receivers with less severe interference. Using an improved high-level mixer can lead to better communications, radar, and navigational equipment for aircraft, maritime, and other applications that share an overcrowded rf spectrum.

## INTRODUCTION

Mixers are used in various communication, radar, and navigational systems to generate electromagnetic signals of higher or lower frequency (at the IF port) by mixing the incoming signal (RF port) with a signal generated by a local oscillator (LO port). This is typically performed by using the nonlinear current-voltage (I-V) characteristics of a diode switch.

Because one or more stages of amplification are typically used downstream of the mixer to increase the voltage of the IF signal, it is important that the mixer not add undesired signals to the desired incoming signal, as these also would be amplified indiscriminately. Diodes with low noise, good turn-on characteristics, low series resistance, high saturation levels, and repeatable electrical properties from device to device are needed and are important characteristics in mixer design that lead to wide dynamic range properties.

The useful dynamic range of a mixer is bounded by its noise level and the level at which the mixer can no longer linearly process the incoming rf signal (the 1-dB compression level); that is, when a 1-dB increase at the rf input port no longer yields a 1-dB change at the IF output port. Because the dynamic range of mixers typically exceeds that of small-signal amplifiers and crystal detectors, mixers are used in the frontend of a communication system (when dynamic range is critical). Thus, mixer performance is central to the overall performance of an rf or microwave receiver system.

Rf signal mixing occurs in semiconductor junctions because of the nonlinearity turn-on characteristics of the I-V curve of a diode, while the saturation part of the I-V curve generates the intermodulation distortion (IMD) products. When two closely spaced rf signals are mixed, the IMD products appear above and below the two signals and are spaced equally between them. The IMD products quickly crowd the spectrum of the desired signal.

When dealing with very strong signals, present mixer designs call for improving the saturation level of mixers by increasing the number of switching elements in a mixer circuit. This is done, for example, by multiple-series diodes in a balanced circuit or by combining mixers with 180-degree or quadrature hybrids. Fabrication and matching of multiple-series diodes is difficult and time consuming, and can add greatly to the cost of fabricating high-level mixers. While high-level mixers also require high LO power levels (and this may not be desirable in certain cases from a power budget standpoint), this is desirable from an IMD product standpoint, because mixer-generated IMD products are usually created when the signal level at the RF port reaches the LO power level of the mixer.

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While only two silicon carbide (SiC) wide-bandgap junctions were needed in this mixing experiment to produce a 27-dBm (LO) mixer, 12 silicon (Si) junctions would be required to obtain the same operating level.

The reduction in the number of diode junctions arises because SiC is a wide-bandgap semiconductor (almost 3 eV), and has a larger turn-on voltage than Si or gallium arsenide (GaAs). A Si Schottky has a 0.3-V turn-on, while a SiC Schottky has almost a 1.0-V turn-on property. This is an increase of almost one order of magnitude in power turn-on requirements. The SiC Schottky is well suited for replacing multiple-series semiconductors that are connected with only one switching element. Other SiC properties are high rf burn-out levels, high breakdown field strength, high thermal conductivity, and a high-saturation electron drift velocity. These characteristics lead to the design of rugged switches. A theoretical analysis of the superiority of SiC devices over Si devices is given by Bhatnagar and Baliga [1]. In addition to SiC, another wide-bandgap material, gallium nitride (GaN), is just becoming available. GaN is being used to make blue light-emitting diodes and should prove equally effective for mixing applications for the same reasons as SiC. However, Schottky diodes with very low loss are difficult to obtain for wide-bandgap materials due to the many epilayer growth problems.

SiC exists in a large number of polytypes that have different crystal properties. They can be formed by the many possible stacking sequences of double layers of Si and C atoms. Presently, 4H, 6H, and 3C (two hexagonal and one cubic phase) are candidates for SiC device fabrication. 3C-SiC has a smaller bandgap (2.2 eV) and slightly lower maximum field strength, but has high electron mobility, like 4H. 6H has a lower electron mobility, hence 4H and 3C are superior to 6H for switching applications. Additionally, it may be possible to grow good-quality 3C-SiC epilayers on AlN-Si substrates (not proven yet), which would result in an alternative approach in fabricating SiC devices on large Si wafers. Unfortunately, stacking faults and double-position boundaries severely limit the use of 3C-SiC.

## CIRCUIT CONFIGURATION

Figure 1 is a schematic of a 500-MHz rf input balanced mixer circuit that was built to test the SiC mixer. It consists of a 50-Ω, 90-degree hybrid circuit. The IF output was set at approximately 100 MHz. The hybrid offers some (limited) isolation between the RF and LO ports, while driving a pair of diodes (there was no attempt to match the diodes to the mixer circuit in either the Si or SiC case). Diode orientation in this case is not important because the diodes are fed 90 degrees out of phase instead of the typical 180 degrees. The main reason for the choice of this circuit was simplicity. Figure 2 is a schematic of the two-tone test setup used to measure the IMD products generated by the mixer when Si and SiC diodes were tried.

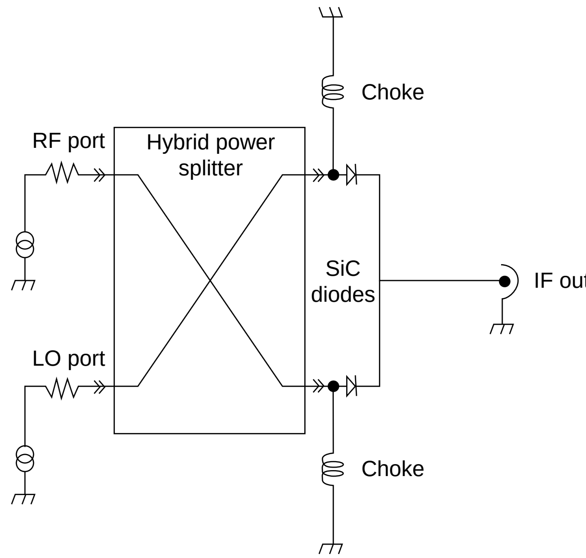


**Figure 1. Rf mixer circuit.**

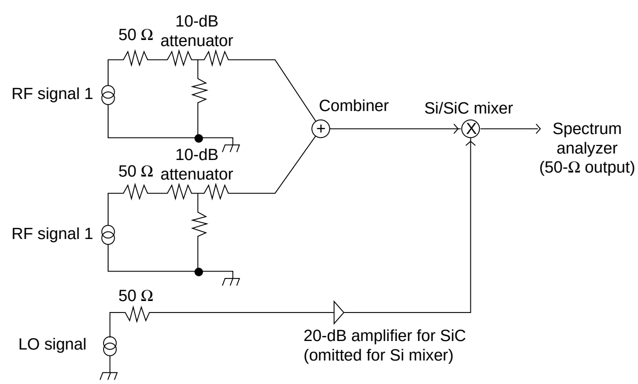


**Figure 2. IMD test setup.**

Figure 3 shows the IF output spectrum when ordinary Si diodes are employed. IMD products up to the 7th order of magnitude can be seen along the sides of the desired signals. Figure 4 shows the IF output spectrum when using SiC Schottky diodes (produced at NASA-Lewis). While conversion loss with the SiC mixer is about 2.5 dB worse than the Si mixer (12 dB vs 10 dB), the SiC mixer has no observable IMD products. Unfortunately, the noise level of the LO generator was also amplified along with the LO signal level, resulting in a noise-floor level that was 20 dB higher. This feature shows how important it is to design low-noise, high-level LO sources when using high-level rf mixers. Low-noise LO sources will be used in a future mixer experiment to determine the exact IMD product levels for the SiC mixers, which are at least 20 dB lower than the Si mixer.

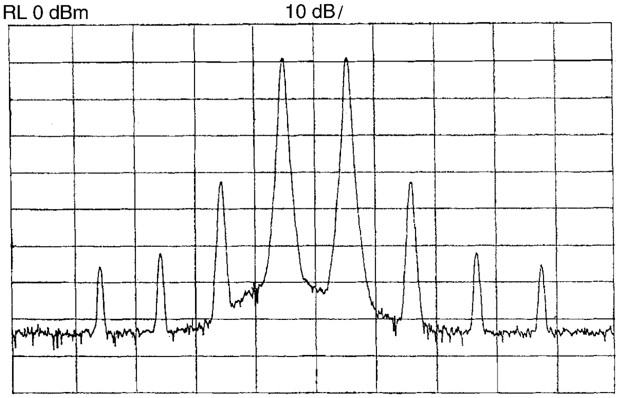


**Figure 3. Si mixer radio frequency spectrum at IF.**

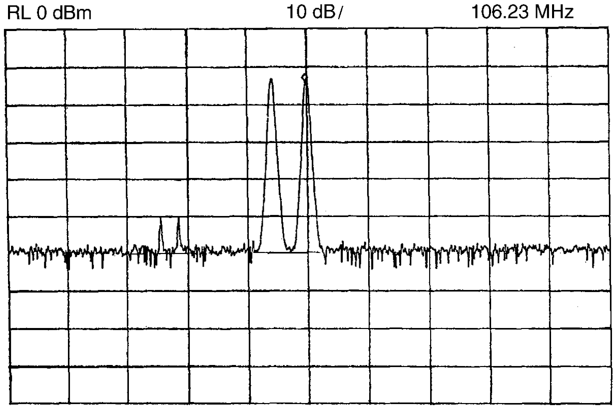


**Figure 4. SiC mixer radio frequency spectrum at IF.**

## SUMMARY

We believe that these are the first mixer experiments involving wide-bandgap materials. We also believe that the measured decrease in IMD products is the result of the higher turn-on voltage of SiC diodes, which shift the diode turn-on characteristics and require a higher LO drive level. Hence, using wide-bandgap semiconductors instead of Si or GaAs diodes provides an alternative approach to the practice of reducing IMD products in rf mixers. The property of lowering IMD products is also useful for developing better transmit/receive (t/r) switches and small-signal rf amplifiers using wide-bandgap semiconductors.

## REFERENCE

1. Bhatnagar and Baliga, "Comparison of 6H-SiC and Si for Power Devices," *IEEE Transactions on Electron Devices* **40** (1993), pp. 645–655.