Design of Slow-Wave Integrated Antenna in Advanced SiGe Technology for FMCW Radar Applications: Analysis of Near-Field Couplings

Sidina Wane[1], Olivier Tesson[1], Serge Bardy[1],Rob van Heijster[2], Raymond van Dijk[2] and Giampiero Gerini[2,3]

[1] NXP-Semiconductors, Esplanade Anton Philips 14906, Colombelles Caen – France
[2] TNO Defence, Security and Safety, The Hague – The Netherlands
[3] Eindhoven University of Technology, The Netherlands

ABSTRACT— **This paper presents an overview of low-cost advanced SiGe based BiCMOS technologies for future RF, Miwrowave and THz applications. Illustrative design examples ranging from elite passives, Slow-Wave On-Chip and On-Package integrated antennas for mm-Wave applications, to Schottky diodes demonstrating supra THz performances are presented.**

I. INTRODUCTION

Progress in Silicon-based technologies [1-3] are rendering possible integration of RF, Microwave and THz applications [4-5] classically implemented using GaAs-based solutions. Perspectives for use of Graphene and Carbone-Nano-Tubes (CNT) in Silicon-based technologies are discussed in [6]. However, low breakdown voltage of silicon transistors together with conductor losses (*signal-power transport*) make power generation and detection at RF, Microwave and THz frequencies extremely challenging. Advanced SiGe technologies enable breakthrough in integration of mm-wave frequencies both in single-chip and multi-chip solutions including phase-array systems [7]. Use of radar systems in civil domain is increasing with emergence of FMCW application for security and automotive car traffic. Recent advancements in SiGe based technologies have enabled integration of FMCW (*Fig.1 shows simplified FMCW block diagram for radar* [8] *with dedicated chip used as ramp generator*) which used to be addressed from III-V compound semiconductors perspective (*e.g., GaAs-based technologies*). Compared to GaAs technologies and to high resistivities of compound semiconductors, silicon integrated circuits are implemented on a conductive substrate which exhibits lossy behavior particularly at mm-Wave frequencies and beyond. Such lossy behavior results in poor radiation efficiency for integrated antenna through different physical mechanisms which can induce electromagnetic couplings jeopardizing system level performances.

In this work, we present an overview of advanced Silicon-based technologies for future RF, Microwave and THz applications. This paper is constructed around two major sections. The first section discusses improved passives (*interconnects, Trough-Silicon-Vias (TSV), inductors, filters, varactors*) in terms of losses, quality-factors and isolation. In the second section, performances of integrated Slow-Wave On-Chip and On-Package antennas are studied for mm-Wave frequencies. Schottky diodes are designed, fabricated and experimentally characterized for future mm-Wave (*including use as mixer in FMCW*) and THz applications.

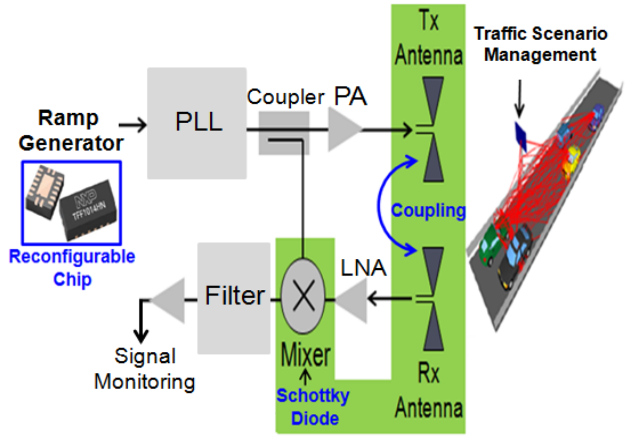


Fig.1: Simplified FMCW block diagram for radar applications highlighting use of dedicated reconfigurable Chip as Ramp Generator (*PLL with variable input frequency*).

II. OVERVIEW OF MAIN RESULTS AND APPLICATIONS

A. *Integrated Passive Interconnects and Filters for RF and Microwave Applications*

One of the key factors that determine the performance of a Monolithic Microwave Integrated Circuit (MMIC) is the possibility to first have good quality passive devices such as inductor, varactors and transmission lines. The second point is related to the on-chip transport of high frequency signals. In fact, immune transports of high frequency signals is especially important when the passive components needed for RF, such as coils and/or decoupling capacitors are integrated together with other digital/analog components on the same die. The proper placement and routing of these kinds of devices is of paramount importance and represents a real challenge for RFIC designers. On the other side, with recent emergence of new 3D interconnect technologies such as TSV, passive interposer designs are also considered to bring high performance MCM applications. Filtering applications have been achieved in that sense showing promising performances for S-band applications. Typical IL of 1 dB (on glass) and 2dB (on Silicon) have been demonstrated on TSV based band-pass filters [9]. Then, shortening the die thickness and thus the via dimension also open the way to millimeter wave applications. Generally, losses within backend devices are mainly driven by the metal type and thickness on one side and the distance to the substrate on the other side. One area of improvement resides in shielding techniques. Significant research efforts have been devoted to develop isolation techniques [10] that limit noisy couplings between sensitive function blocks and substrate. Among main isolation techniques, proposed in the scope of MMIC applications, are guard-ring barriers, deep-trenches, triple-wells and Faraday cages.

NXP in-house BiCMOs SiGe:C process is already able to provide good-quality inductors used within diverse applications. Thick top Al layer is considered to design the inductor windings together with a distance of 10µm from the substrate. Furthermore DTI (Deep Trenches Isolation) are implemented below the coils to break eddy current in the substrate. Experimental and simulated variations of self-inductance and quality factors are reported versus frequency in Fig. 2.

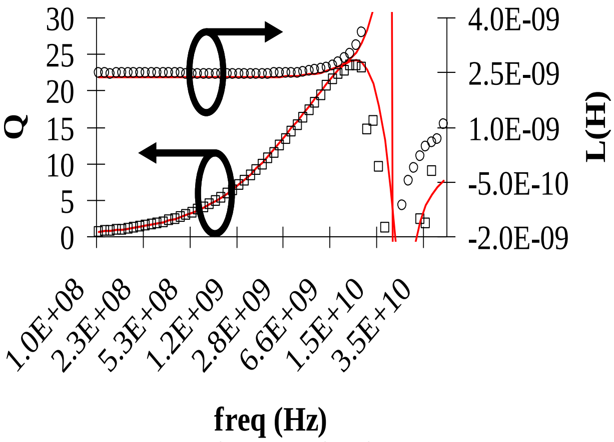
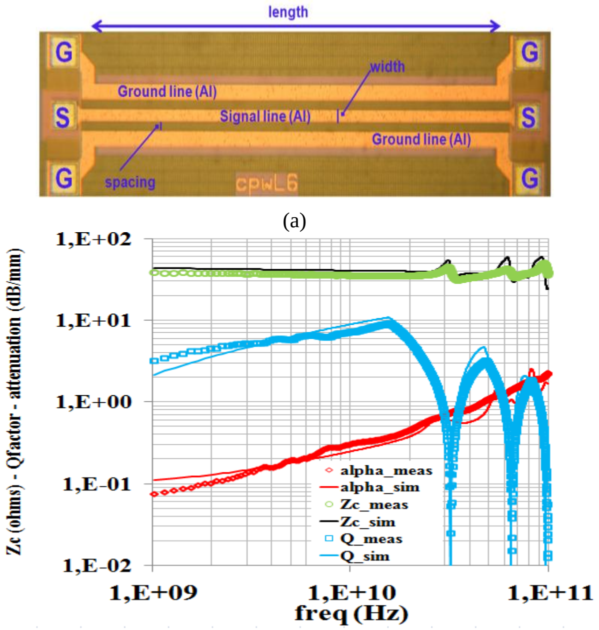


Fig. 2 -Variations versus frequency of Self-Inductance value L and quality factor Q. __: simulation, square symbols refer to measurement.

Transmission line elements are also of particular relevance for millimeter wave application especially for signal transport and filtering application. NXP process allows designing conventional microstrip and coplanar type of lines compliant with process rules. In addition to them, slow-wave coplanar lines are also considered to reduce the device physical size and thus reduce the losses according to Fig.3 (a). In fact, to shield the line and thus reduce and prevent the losses within the substrate, a metal shield is implemented in order to block the electric field penetration inside the lossy substrate. On the other side, a patterned design is adopted to be compliant with design rules and also to break current loops in it. So, these loops can have a significant impact on line attenuation. Measurement results together with EM simulations are provided on a 50Ω in Fig.3(b). From the measurement data, an average attenuation of *0.38dB/mm@*40 GHz is observed which makes this line a really good candidate for frequency selection applications (*attenuation values lower than 0.3 dB/mm@50 GHz can be achieved*). The need for high-quality integrated capacitor for coupling and filtering applications is also a key point for such technology.



(a)

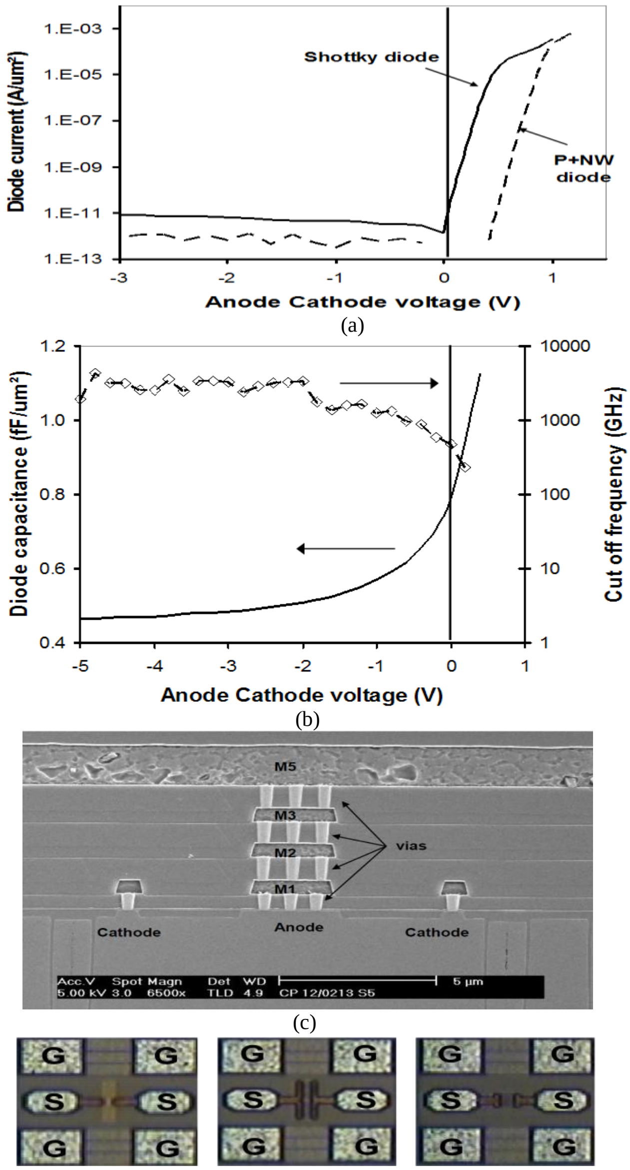
(b)

Fig. 3 - Layout pattern of the considered slow-wave transmission line (a), comparison between measured and simulated data vs. frequency for transmission line characteristic impedance Zc, attenuation alpha and quality factor Q (*length=2000µm, width=15µm, spacing=8.3µm*), (b).

Capacitors must be as dense as possible, present a high breakdown voltage together with high quality factors. A MIM capcitor with area density of 0,75 nF/mm^2 has been developped. Devices with capacitance value down to 6,5 fF have been measured against frequency. Their quality factor is greater than 120 @ 40 GHz allowing high performances Ka-band operations. The tight requirements in terms of Phase Noise (PN) imposed by communication standards have also led to the development of high quality varactors. In the low GHz frequency range, varactors show Q-factor considerably higher than inductors and hence they have a tight influence on integrated oscillators PN. However, for frequencies of 10 GHz and above, the varactor Q-factor can seriously limit the resonator performances and consequently the oscillator PN. This is why a good comprimise must be found between Tuning Range and quality factor. A junction varactor has been developped in that perspective and mesaured between 0 and 5V as a function of the frequency. This new varactor topology outperforms state of art [11] with Q-factor of 30 at 40 GHz -120 fF device- and Q-factor of 180 at 5 GHz.

B. On-Chip, On-Package Integrated Antennas and Schottky Diodes for RF, Microwave and THz Applications

This section presents design solutions for Antenna-on-Chip and Antenna-on-Package (*with Bond Wire elements*) and Schottky diodes using advanced NXP SiGe:C technology. Schottky diodes are essential devices in mm-waves and THz applications. They are mainly used for power detection, signal mixing and/or



(a)

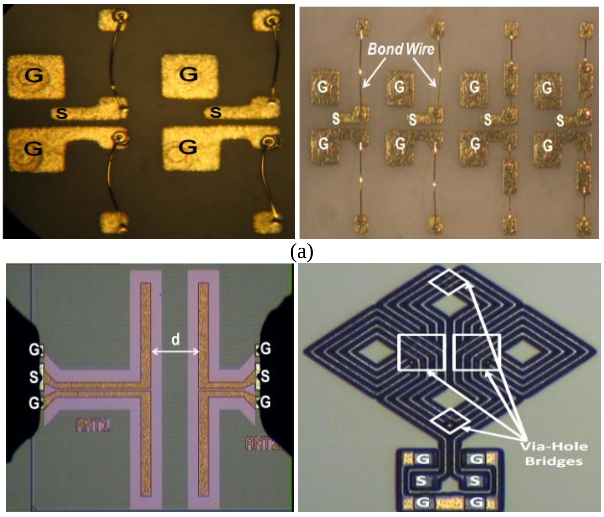
(b)

(c)

(d)

Fig.4 Measured current density versus bias voltage for Schottky diodes compared to conventional P+NW silicon diodes (a), measured capacitance-voltage characteristics and cut-off frequency curves of Schottky diodes (b). Cross-section microphotograph (c) of designed and characterized Schottky diode for mm-Wave mixing and THz detection. Microphotograph of various Schottky diodes topologies (d) designed to investigate impact of geometry [6] on THz performances.

frequency down conversion. Fig.4(c) shows cross-section of designed and fabricated Schottky diodes for mm-Wave mixing and THz detection, where diffusion area without implant forms a Silicide-Si junction. Ohmic contacts on n-well form the n-terminal. The Schottky diodes are equipped with a P+ guard ring in order to limit the effect of the shallow trench oxide edges on reverse leakage current in the vicinity of the Silicide-Si junction. The implementation requires no process modifications. Despite the presence of this P+ guard ring, the Schottky diodes are demonstrating supra THz performance (Fig.4(a),(b)) with an average cut-off frequency in the order of 1.1THz over a 0 to 5V reverse bias range.



(a)

(b)

(c)

Fig.5: Microphotographs of integrated Bond-Wire [5,13] (a) Antennas for mm-Wave applications, coupled On-Chip Dipole (b) antennas and Silicon-based On-Chip RFID antenna (c).

Design, modeling and fabrication of on-package and on-chip antennas in Fig.5(a),(b),(c) are proposed for mm-Wave and RFID applications. Fig.6 shows insertion loss of on-chip/on-package antenna working at 50GHz (*antenna-A*), 60 GHz (*antenna-C*), and 77GHz (*antenna-B*) with associated Near-Field couplings. For the full-wave EM modeling setup, the resistivity of the silicon substrate is taken variable with non-uniform profiling along the vertical direction.

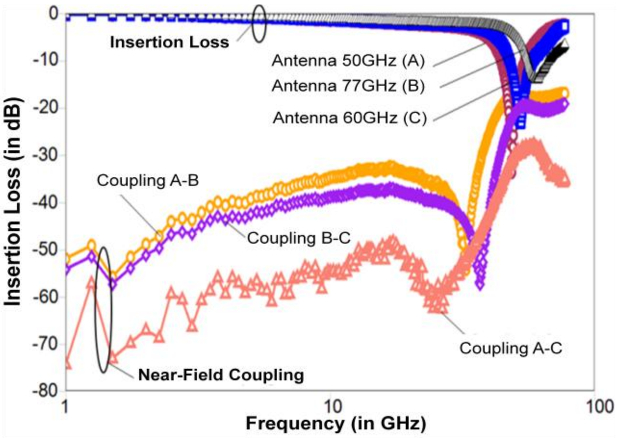


Figure 6: Measured insertion loss of 50GHz, 60GHz, and 77GHz and associated Near-Field couplings. Near-Field couplings are characterized for various antennas separation distance.

Fig.7 represents real and imaginary parts of extracted effective permittivity as function of silicon substrate conductivity, for a CPS line (*inset of Fig.7*), showing existence of a slow-wave region (*high losses*) with substrate conductivity between 100S/m and 1000 S/m.

In the electromagnetic simulation setup, the resistivity of the silicon substrate and the conductivity of the buried doped layer are considered as variable parameters. Incorporation of variable doping profiles in electromagnetic modeling approaches remains very challenging.

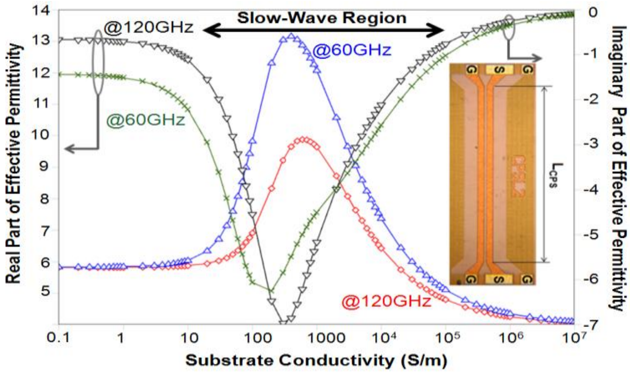


Fig.7 Real part and imaginary part of complex Effective Permittivity for on-chip CPS transmission line as function of Silicon conductivity σ_{Si} (in S/m) showing Slow-Wave effects [12] .

In [12] impact of Epitaxial layer conductivity on antenna insertion loss, demonstrating possibility to take benefit of active layer doping profile attributes for antenna performances optimization (*slow-wave phenomena*) is presented. Although high value for the real part of the effective permittivity can be attractive for size reduction it might bring some difficulties for antenna On-Chip leading to poor radiation efficiency. To overcome radiation efficiency limitations, integrated Bond-Wire antenna [13] are seen as possible alternative solutions. The concept of Chip-Package "*Co-Design*" antenna is discussed in [14] where physics-based broadband equivalent circuit modeling is proposed for Chip-Package-Antenna system "*Co-Analysis*" and verification (EMC/EMI).

Fig.8 depicts comparison between measurement and full-wave electromagnetic simulations for On-Chip RFID antenna showing satisfactory agreement. The RFID antenna achieves relatively high inductor value in the order 100nH at low and moderate frequencies for a resonant frequency of 480 MHz.

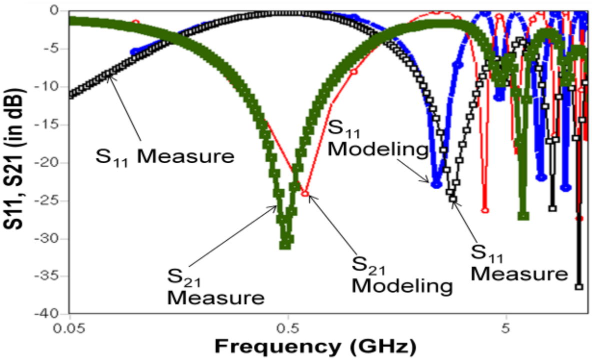


Figure 8: S_{11} and S_{21} parameters for On-Chip RFID antenna in Fig.6(c): comparison between measurement and full-wave electromagnetic simulation.

III. CONCLUSION

Advanced SiGe BiCMOS technologies offering elite passive devices and efficient building blocks for future RF, Microwave and THz applications are investigated in the perspective of low cost solutions. Use of Bond-Wire antenna Chip-Package co-design is seen promising for antenna efficiency enhancement. Significantly thinner substrate is required for functionality of the mm-Wave and THz antennas to avoid spurious slab modes. Zero mask adder Schottky diodes with low leakage current, low junction capacitance, large breakdown voltage and with cut-off frequencies in the THz range are demonstrated in advanced SiGe technology.

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