Nanotechnology-Enabled Additively-Manufactured RF and Millimeter-wave Electronics

Aline Eid, Bijan Tehrani, Jimmy Hester, He Xuanke, and Manos M. Tentzeris
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, USA.

***Abstract*—This paper covers examples of state-of-the-art nanotechnology-empowered materials relying on additive manufacturing techniques for the ultra-low-cost fabrication of flexible radio frequency (RF) and millimeter-wave (mm-wave) wireless electronics and sensors. First, a look into the utilization of carbon-based nanomaterial inks such as carbon nanotubes inks for chemical sensing applications is provided, reporting the most sensitive inkjet-printed ammonia and dimethyl methylphosphonate (DMMP) vapor sensors. These sensors are then integrated with very high-performance flexible printed antenna structures for emerging Internet of Skins (IoS) and 5G applications. The focus is then shifted towards the realization of fully inkjet-printed passive devices including Metal-Insulator-Metal (MIM) capacitors and spiral inductors. Finally, the importance of nanomaterial-based inks is highlighted in the development and fabrication of high-performance fully inkjet-printed 3D interconnects for wireless mm-wave packaging solutions. Conductive silver nanoparticle and dielectric polymer-based inks are utilized to realize this interface between a die and its packaging substrate, opening new doors for the next generation of advanced, high-performance and ultra-low-cost microelectronic manufacturing and packaging solutions.**

I. Introduction

INKJET printing is an additive manufacturing technology that has been gaining large consideration over the last decade for being at the base of the flexible electronics field growth. Printing technologies allow for rapid prototyping on a wide variety of substrates, a capacity to work in large-area roll-to-roll approaches while preserving a low material wastes, low operation cost and environment friendliness [1]. Generally, inkjet technology has been used to fabricate low-frequency single-layer components such as antennas, and lumped components for RFID applications. However, recent developments in electronic ink formulation and inkjet printing have opened the door to the realization of passive devices by offering efficient ways to producing multi-layer components at high frequency such as parallel plate capacitors, multilayer antennas, and complex RF sensors [2], [3], [4]. The additive inkjet printing technology allows a noncontact process that can successively deposit multiple layers of different materials without disturbing the previously deposited layers, as opposed to conventional methods relying on a sequence of photolithography and etching steps that uses harsh chemicals and produces a lot of waste materials. Another breakthrough enabled by inkjet-printing is the ability to preserve a low temperature fabrication process (<200°C), thus offering a wide variety of substrates, that outperforms techniques such as chemical vapor deposition (CVD) requiring heating of the substrate to about 1000°C. This paper shows a wide variety of applications enabled by inkjet printing that involves the direct deposition of a wide range of materials such as conductive, dielectric, and semiconductor inks. Sec. II of the paper covers the realization of carbon-based devices for gas detection. Carbon nanotubes (CNTs) and graphene have the ability to change their electrical properties after absorbing a chemical specie. A very sensitive fully inkjet-printed CNT sensors for ammonia and DMMP detection are reviewed. In Sec. III, the focus is shifted towards the role of inkjet printing in the fabrication of RF passive devices such as Metal-Insulator-Metal (MIM) capacitors and spiral inductors. Sec. IV shows a groundbreaking advancement in the world of packaging technologies through inkjet printing enabled 3D interconnects. The use of silver lines and dielectric ramps allows the interface realization of a very small feature die to its packaging substrate. The paper is finally concluded in Sec. V.

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II. Flexible, Inkjet-Printed Carbon-Nanomaterials-Based Sensors

Smart Skins on the IoS present a huge potential for the enabling of large-area, ubiquitous chemical sensing and hazard monitoring and alarm systems. Displaying a combination of low profile, energy-autonomy, wireless communications, localization, identification and chemical and bacteriological sensing capabilities, such devices are enabling a quantum-leap in airborne chemical surveillance systems. High-performance sensors naturally lie at the core of such nodes of the IoS. This section will present examples of fully-printed low-cost ultra-low-power and high-performing resistometric sensors whose design was optimized for Smart Skin devices.

A. Functionalized CNT Nerve Agent Sensor

The first examples of such sensors for IoS devices come in the form of ammonia-sensitive resistometric components, fabricated using exclusively an inkjet printing process. The first of these sensors, first reported in [5], employed a single-wall carbon-nanotubes (SWCNT) ink used to print a reactive SWCNT film, which was then chemically functionalized with different groups. Finally a silver-nanoparticles-based ink was used to print metallic inter-digitated electrodes to electrically interface this chemically reactive film. As shown in Fig. 1, the sensors displayed the sensitivities to 2.5ppm of DMMP, a nerve agent simulant. This result demonstrated the ability of functional groups to enhance the performance of printed sensors by orders of magnitude. Later efforts not only enhanced the sensitivities of such printed sensors, but uncovered the contact-mediated mechanism likely at the source of such

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changes in performance, as well as the additional importance of the nature of the electrodes used in these structures [6].

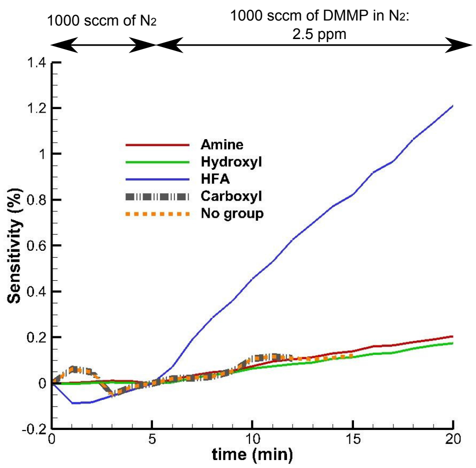

Fig. 1: Sensitivity of the fully inkjet-printed SWCNT sensors to 2.5ppm of DMMP, with different functional groups.

B. SWCNT-PABS Ammonia Sensors for Real-Time Wireless Gas Monitoring

A printed ammonia sensor using PABS-functionalized printed SWCNTs was integrated into the energy autonomous ultra-low power system reported in [7] and shown in Fig. 2, which was demonstrated to enable real-time sensing of the ambient presence of ammonia, through its connection to the modulation frequency of a long-range mm-wave backscatter tag.

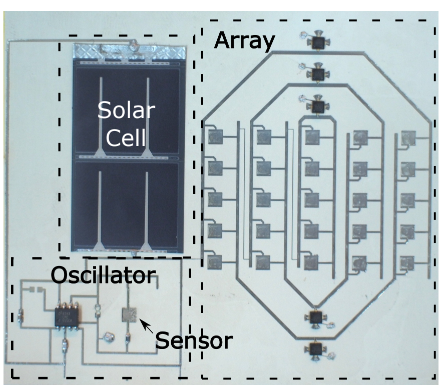

Fig. 2: Picture of the inkjet-printed, flexible, energy-autonomous Smart Skin tag used for long-range real-time gas monitoring. [7]

The response of the sensor, displaying an extremely-high measured sensitivity of 12% to a mere 2ppm of ammonia–25 times smaller than the general OSHA Permissible Exposure Limit (PEL) of 50ppm–was remotely measured in real-time (shown in Fig. 3), thereby demonstrating its ability to provide an ultra-low delay, low-cost, energy-autonomous and low profile skin for high-density chemical alert systems of the IoS.

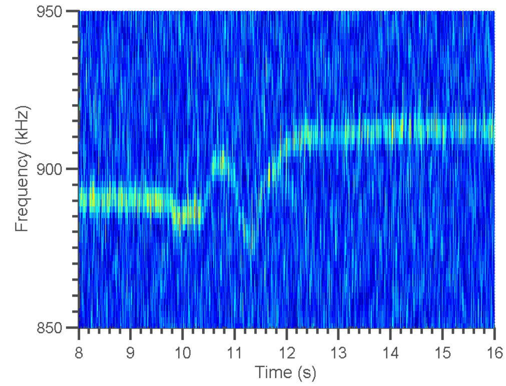

Fig. 3: Remotely-measured response of the device of Fig. 2 to an illumination with ambient ammonia. [7]

III. Inkjet-Printed Inductors and Capacitors

Passive components are an integral component of RF circuits and electronics as they are utilized for signal conditioning, matching and filtering. Typical RF systems utilize bulky surface mount components or lossy on chip components for passives. Utilizing inkjet printing capacitive and inductive RF structures can be realized to enable low-profile and flexible systems in an efficient additive fashion. Using the multi-layer technology of inkjet printing, passive structures that previously required multi-layer lamination can now be done on a single process run. In addition, as an additive manufacturing method, only the materials required are used reducing waste as opposed to traditional methods of photomasking and etching.

A. Metal-Insulator-Metal Capacitors

The most common type of capacitor is the Metal-Insulator-Metal (MIM) capacitors where two metal layers are separated by a dielectric insulator. This type of topology can be easily integrated with inkjet printed technology as metal and dielectrics inks can be easily printed onto various substrates, greatly reducing the complexity of design. Using highly conductive silver nanoparticle inks as the metal layers, and PVP for thin film ($> 0.5\,\mu\text{m}$) and SU8 ($>$ 2μm) a wide range of capacitances can be created by changing the insulator thickness by printing multiple layers.

In addition to printing multiple layers, inkjet printing can also allow for printing on many different substrates. Inkjet printed MIM capacitors on polyimide can achieve a Self Resonant Frequency (SRF) >1 GHz and similar capacitance per unit area as bulk chip capacitors [2]. Inkjet-printed MIMs on a host silicon substrate, as shown in Fig. 4 show 1.2 GHz SRF and a capacitance of 33 pF/mm [8].

B. Spiral Inductors

Inductors can also be realized utilizing inkjet printing with the most common type of inductors being spiral inductors. These inductors are typically fabricated on CMOS processes by laying out spiral conductive traces and bridging the center tap to the edges. This is an excelled application for inkjet printing as it is inherently a multi-layer fabrication process.

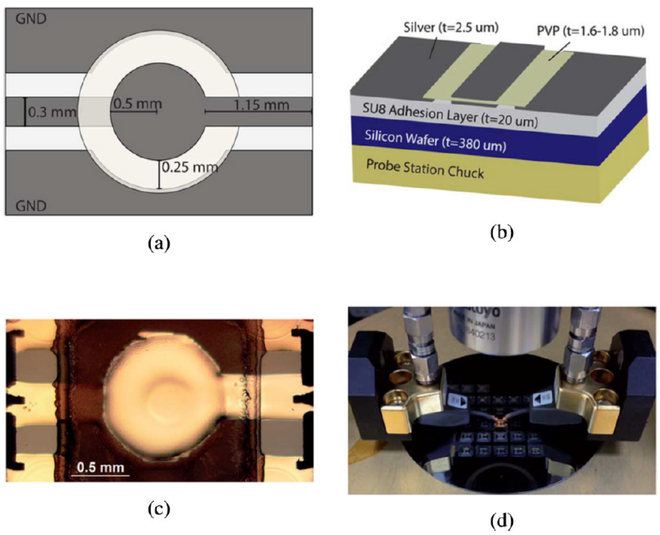

Fig. 4: Fully printed MIM capacitors on Si substrates. (a) Top view (b) Layer stackup. (c) Fabricated sample. (d) On wafer measurements.

Spiral silver conductive lines were first printed on flexible LCP substrates followed by printing of a dielectric bridge with a via which was later filled in with additional silver nanoparticle ink to bridge to the outside traces. This creates the two port spiral inductor as shown in Fig. 5. By changing the spiral turns, the inductance can be changed allowing for the ease of creating custom inductor values. The quality factor of the printed inductors, shown in Fig. 5 varies from 8.5 to 21 at 1 GHz [9], depending on the number of silver nanoparticle layers printed, demonstrating the highest quality factor and inductance values reported in printed passives literature. With these printed passive structures, future work of fully additively-manufactured RF systems is possible and could allow for drastic decrease in cost of integration and customizability.

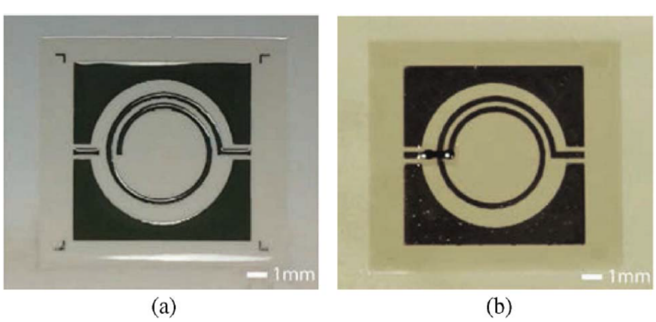

Fig. 5: (a) 1.5 turn sprial inductor without bridge, (b) with bridging to output trace.

IV. Additive Manufacturing for High-Performance 3D RF Interconnects

Practical RF and mm-wave wireless systems rely heavily on both component and board-level packaging technology. Areas of interest include the development and integration of materials with low dielectric loss, realizing low-loss interconnects, and integrating multiple circuit components in system-on-chip (SoC) and system-in-package (SiP) design schemes. Specifically, realizing efficient RF interconnects with discrete active devices can be a challenging task both electromagnetically and mechanically, highlighting concerns for emerging flexible and conformal mm-wave systems. Typically, interconnection between a wireless chip and a packaging substrate, such as a lead frame, is achieved through thermosonic wire bonding techniques. These wire or ribbon bond interconnects are inexpensive and used widely throughout industry, however passive compensation circuits are typically required to account for the high series inductance (approximately $1\,\mathrm{nH\,mm^{-1}}$) found in bond wires [10], [11]. The development of efficient 3D interconnects is essential for wireless SiP design schemes, where active components (radios, amplifiers, switches) and passive components (antennas, bypass capacitors, filters) are all integrated within a single package to allow for device miniaturization and subsequently reduced system losses. The following section will focus on the development of low-loss, application-specific 3D RF interconnects using metallic nanoparticle-based inks with additive inkjet printing fabrication technology for mm-wave wireless SiP packaging.

Additive manufacturing technologies such as inkjet and 3D printing are currently being evaluated as candidates for the development of low-loss RF interconnects replacing standard wire and ribbon bonding techniques within wireless systems [12], [13], [14]. Low-viscosity silver nanoparticle-based inks enable the patterning of conductive features on a wide variety of substrates in a low-temperature fashion, with thermal sintering of the printed nanoparticle features taking place below $200\,^{\circ}\mathrm{C}$. This process eliminates the thermosonic bonding process used with wire and ribbon bonding, which consequently reduces the physical and thermal stresses placed on a die during the interconnection process. Additionally, the material compatibility constraints present with bonding techniques are eliminated due to the drop-on-demand nature of inkjet printing metallic conductors.

A cross-section schematic of inkjet-printed 3D ramp interconnects with a die is shown in Fig. 6a. The fabrication process for these fully-printed interconnects is as follows: first, an SU-8 photoresist-based dielectric ink is printed to pattern 3D ramp structures bridging the plane of the packaging substrate to the top plane of the die. After the 3D ramps are patterned and cured through thermal baking and ultraviolet (UV) light cross-linking, a silver nanoparticle-based ink is printed to pattern coplanar waveguide (CPW) RF interconnects directly onto the printed dielectric ramps, providing a $50\,\Omega$ RF interconnect for a surface mount die. A taper in the dimensions of the CPW line is included to preserve $50\,\Omega$ impedance from the packaging substrate up to the die. Finally, thermal sintering takes place at $180\,^{\circ}\mathrm{C}$ for $1\,\mathrm{h}$ in order to achieve conductive features maintaining a low-temperature process. Fig. 6b–d show images of fully-printed 3D ramp interconnects for integration with wireless devices on the

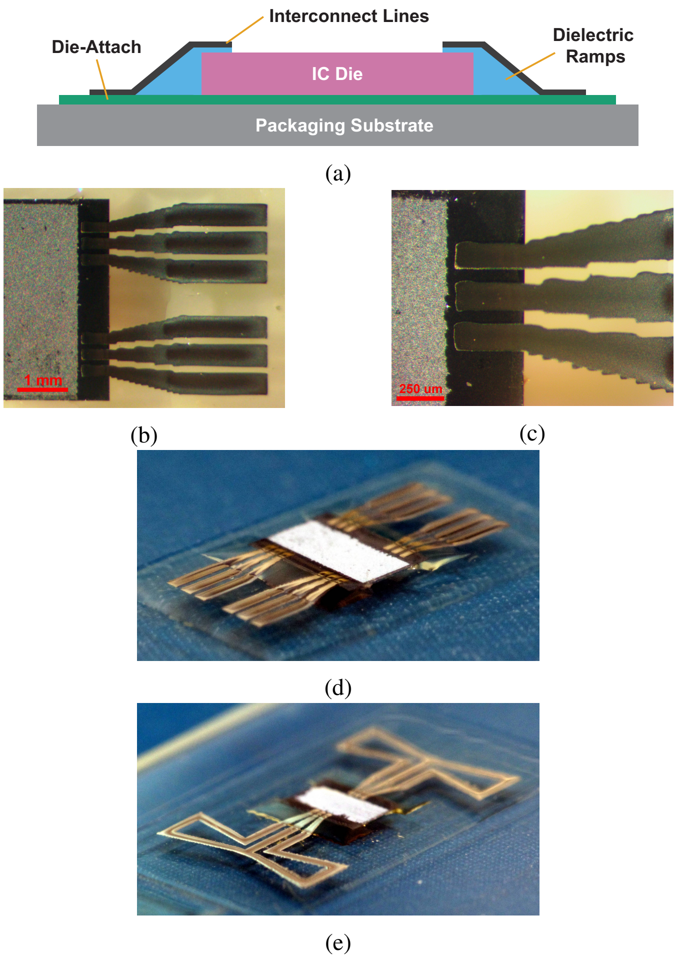

Fig. 6: Inkjet-printed 3D RF interconnects: (a) Cross-section schematic of printed RF interconnects, (b) and (c) detail micrographs of inkjet-printed CPW interconnects, (d) perspective image of fully-printed RF interconnects, (e) perspective image of fully-printed RF interconnects with printed bowtie slot antennas [12].

die level. S-parameter measurements of these interconnects yield a line loss of $0.6\,\mathrm{dB\,mm^{-1}}$ to $0.8\,\mathrm{dB\,mm^{-1}}$ at $40\,\mathrm{GHz}$ along with an inductance of $0.4\,\mathrm{nH\,mm^{-1}}$ to $0.5\,\mathrm{nH\,mm^{-1}}$, yielding approximately half of the inductance of a typical wirebond [10].

As a proof-of-concept, an SiP slot bowtie antenna is designed for direct integration with the printed 3D ramp interconnects, operating within the $24\,\mathrm{GHz}$ ISM band. This demonstration, shown in Fig. 6e, highlights the application-specific advantage of additive printing technology, where a single tool is capable of interconnecting wireless dies with printed peripheral components, including antennas and other passive elements. Integration with active Ka-band devices ($26.5\,\mathrm{GHz}$ to $40\,\mathrm{GHz}$) is currently targeted to further evaluate the effectiveness of inkjet printing nanoparticle-based ink materials for mm-wave wireless packaging solutions [14].

V. Conclusion

This paper has reviewed the recent nanotechnology-enabled additively-manufactured RF and millimeter-wave electronics. The presented structures prove the potential applications of inkjet printing with nanomaterial-enabled inks such as conductive, semi-conductive and dielectric inks. We have reported the realization of the first fully inkjet-printed, highly sensitive carbon-based sensors for ammonia and DMMP detection. In addition, we have emphasized the role of multi-layer nanoparticles-based inks printing to enable the low-cost manufacturing of RF passive devices and 3D system packaging.

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