Multi-Layer RF Capacitors on Flexible Substrates Utilizing Inkjet Printed Dielectric Polymers

Benjamin S. Cook, *Student Member, IEEE*, James R. Cooper, *Student Member, IEEE*, and
Manos M. Tentzeris, *Fellow, IEEE*

***Abstract*—Flexible multi-layer inkjet printed capacitors that have a self resonant frequency above 3 GHz are demonstrated for the first time utilizing two custom formulated polymer-based dielectric inks. The formulation and characterization of both dielectric inks for optimal viscosity and film thickness are performed. The frequency dependent capacitance and quality factor (Q) are presented along with a study on the repeatability and measures to improve the quality factor of printed passives.**

***Index Terms*—Flexible substrates, inkjet printing, inkjet printed capacitors, multi-layer capacitor, RF passives.**

I. INTRODUCTION

INKJET printing as an electronics fabrication technology has attracted significant attention over the last decade as a method to fabricate passive and active components. Printing of electronics allows for rapid prototyping, low material wastes, and does not require clean room environments. Conventional methods of fabricating multi-layer passive structures such as metal-insulator-metal (MIM) capacitors, requires a sequence of photolithography and etching steps which use harsh chemicals and waste a large amount of material in the subtractive processing. Inkjet printing, however, is a purely additive and non-contact process meaning it only deposits the required material, and can successively deposit multiple layers of different materials without disturbing the previously deposited layers. This makes the process very attractive for multi-layer printing of RF components.

Up to now, low-frequency passives including resistors, capacitors, and inductors have been demonstrated in the literature up to 10 MHz utilizing the inkjet process [1]–[3]. However, multi-layer printed MIM structures have yet to be demonstrated and optimized for operation at microwave frequencies through several GHz. Printed microwave capacitors on flexible substrates have a wide variety of applications, especially in printed wearable systems which currently require the use of discrete mounted components [4].

This work includes the optimization of two polymer-based dielectric inks for inkjet printing multi-layer RF capacitors that have self resonant frequencies of over 3 GHz. The inks which are optimized for the Dimatix printer line are compared for layer thickness, capacitor yield due to pinholing, or shorting of the dielectric, and capacitor performance including SRF and Q.

II. PREPARATION OF DIELECTRIC INK

Two separate polymer-based dielectric inks utilizing the polymers SU-8 ($\epsilon_r = 4$) [5], and poly(4-vinylphenol) (PVP) ($\epsilon_r = 3$) [6] are formulated for printing multi-layer MIM structures on the Dimatix DMP-2800 inkjet printing platform. The two polymers are chosen as they have strong chemical resistance after cross-linking, which is the process of linking polymer chains in a chemical reaction, making them resistant to the solvents of following printed inks. As the Dimatix printer requires an ink with viscosity of approximately 7–12 cP to print reliably, both inks are optimized to have a viscosity within this range. While high permittivity inks have been demonstrated in the literature, they are not stable enough to be used in long term industrial applications [3]. The inks in this work are designed to perform well over a period of several months when filled into an ink cartridge.

A. SU-8 Ink Formulation and Processing

SU-8 is commonly used as a photoresist, and has the two advantages of low-temperature UV cross-linking, and high polymer content by weight while maintaining a low viscosity [7]. The higher polymer content by weight allows for thicker and more uniform layers. To formulate the ink, SU8 2002 and 2005 from Microchem Corp. containing 29% and 45% solid content by weight respectively in the solvent cyclopentanone are mixed in an 80% to 20% ratio by weight to obtain a stable ink with a viscosity of 9 cP measured on a Gilmont Falling Ball Viscometer. The SU-8 ink is cross-linked by exposing to UV and then heating to 50 °C for half an hour.

B. PVP Ink Formulation and Processing

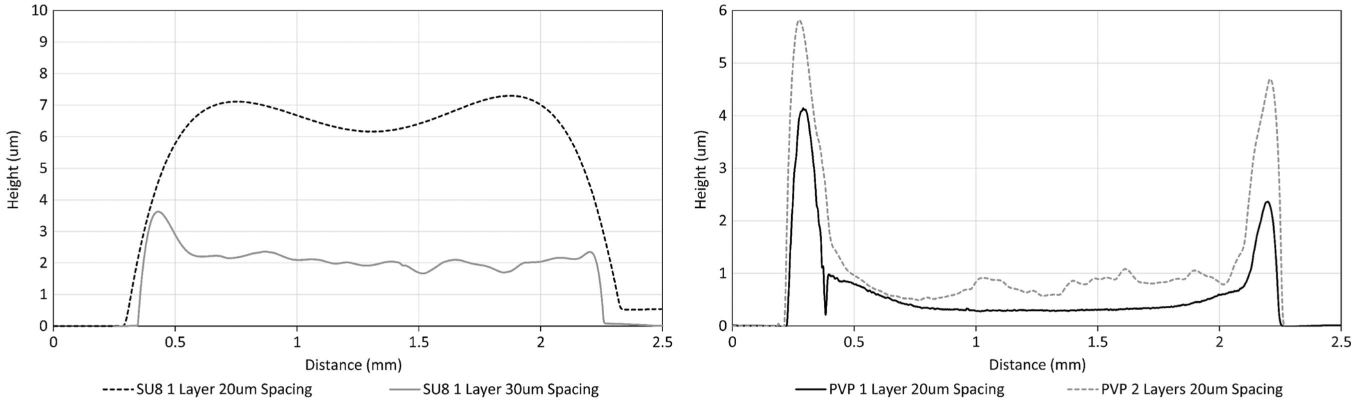
PVP is commonly used as a spin-coat dielectric layer for printed field effect transistors and has been demonstrated to be printable [2]. PVP ink has a higher viscosity at a low polymer concentration by weight in the solvent 1-Hexanol which allows for thinner dielectric layers than with SU-8. To formulate the ink, 0.55% PVP powder (Sigma Aldrich 436216) by weight are added to 1-Hexanol (Sigma Aldrich 471402), with the addition of 0.05% by weight poly melamine-co-formaldehyde (Sigma Aldrich 418560) as a heat activated cross-linker. The PVP ink is cross-linked by ramping the temperature to 180 °C for 5 min.

Manuscript received January 28, 2013; revised April 03, 2013; accepted April 18, 2013. Date of publication June 10, 2013; date of current version June 27, 2013. This work was supported by grants from the National Science Foundation and NEDO.

The authors are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308 USA (e-mail: benjamin.cook@gatech.edu).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2013.2264658



(a) (b)

Fig. 1. Measured dielectric thickness of (a) printed SU-8 ink, and (b) printed PVP ink.

TABLE I
INK CONDUCTIVITY WITH DIFFERENT SINTERING PARAMETERS

PVP % Weight in 1-Hexanol	0	5.5	6.5	10
Viscosity [cP]	0.71	8.93	20	29
SU-8 % Weight in Cyclopentanone	0	29	32.2	45
Viscosity [cP]	1.29	7	8.6	50.6

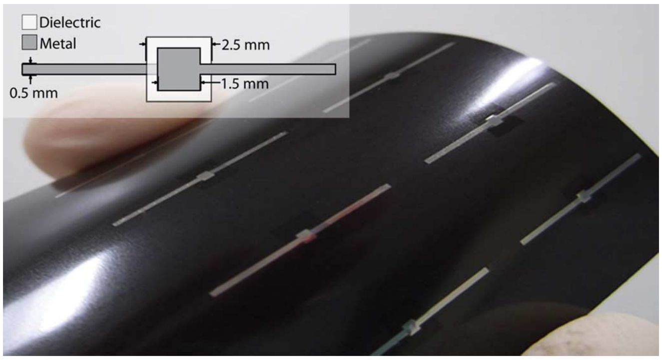


Fig. 2. Array of PVP-based inkjet printed capacitors on flexible polyimide.

C. Printed Dielectric Film Properties

Both inks are printed onto a flexible polyimide substrate with drop spacings of 20 and 30 μm and then cross-linked to determine the optimal film printing process for each ink. A Dektak profilometer is then used to measure the cross section of the printed thin films (see Table I).

The printed SU-8 produces thick, and relatively uniform films due to the high solid content in the ink. As shown in Fig. 1(a), with 30 μm drop spacing the average single layer film thickness is 2 μm while at 20 μm spacing the film thickness increases to 6 μm.

The printed PVP produces much thinner layers due to the lower solid content as seen in Fig. 1(b), and demonstrates a "coffee ring" edge effect due to fast solvent evaporation and the low solid content by weight. At 30 μm spacing the films are discontinuous, so 20 μm spacing is used which produces 400 nm average thickness films with a single printed layer, and 800 nm films with two printed layers.

III. PRINTED METAL INSULATOR METAL CAPACITORS

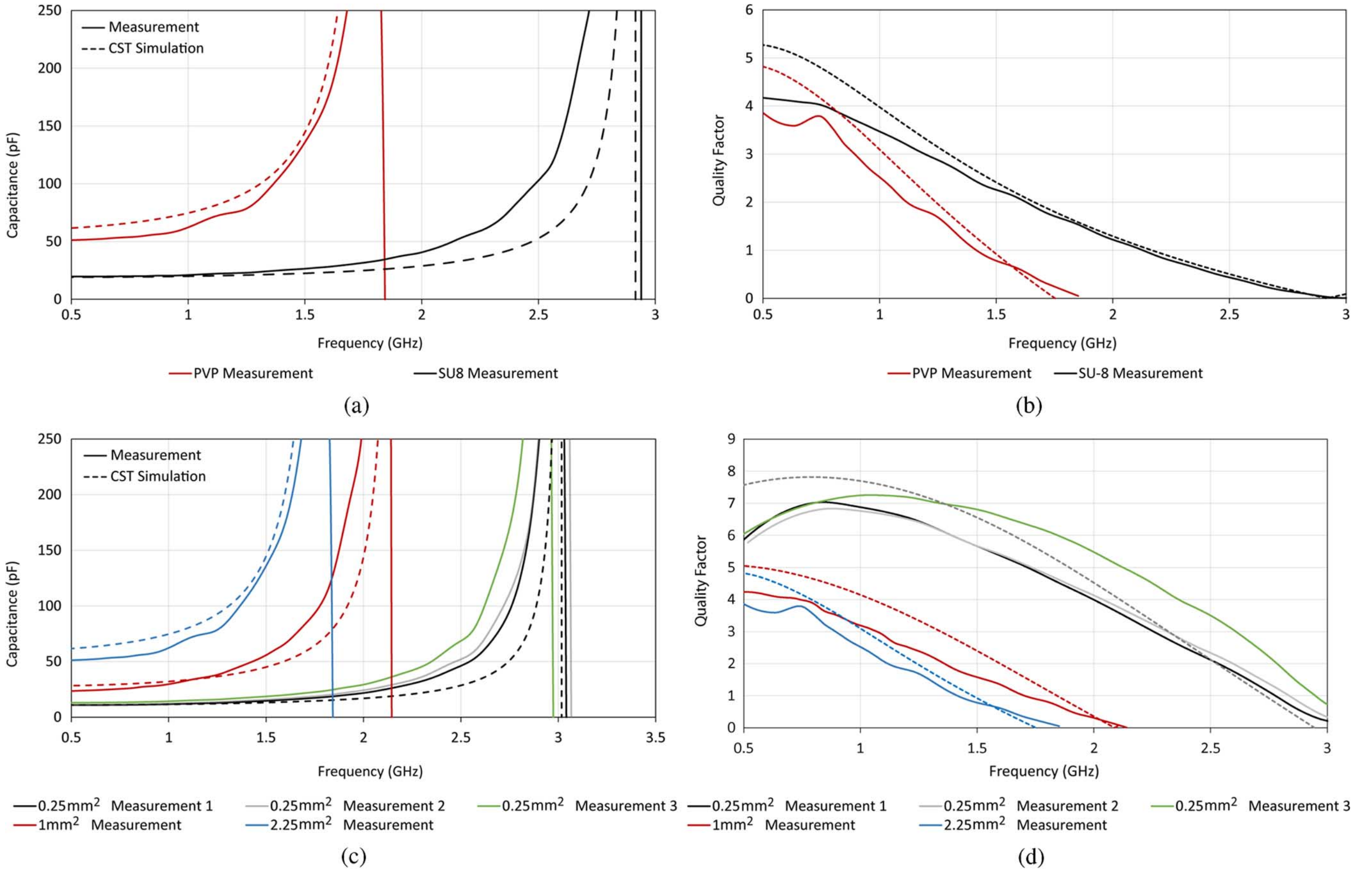
To fabricate the multi-layer capacitors, three layers of Cabot CCI-300 silver nanoparticle ink are printed and cured at 120°C for 1 hour in an oven to form the bottom plate with a 1.5 μm thickness and a conductivity of approximately $5 * 10^6$ S/m [8]. The dielectric layer is then printed and cross-linked, followed by the printing and curing of three more layers of silver nanoparticle ink to form the top plate as shown in Fig. 2.

To prevent shorting due to pin-holing, caused by microscopic bubbles in the dielectric, two layers of dielectric are printed with drop spacings of 30 μm for SU-8 and 20 μm for PVP. This yields dielectric layers of approximately 4 and 0.8 μm respectively.

Using the optimized printing process described previously, microstrip capacitors are fabricated utilizing both inks. SMA connectors are mounted using a silver epoxy and the S-parameters are measured using a Rhode and Schwartz ZVA-8 VNA. A printed TRL calibration kit utilizing the same fabrication process as the capacitors is used to remove the effects of the connectors and feed lines and move the reference plane to the edge of the printed dielectric. The frequency dependent capacitance is extracted directly from the de-embedded S-parameters.

The simulation results from Computer Simulation Techology's (CST) full-wave frequency domain solver are plotted along with the de-embedded measurement results for the printed capacitors with 1.5 × 1.5 mm^2 pads in Fig. 3. The capacitance of the SU-8 based capacitor is lower at 20 pF and has a self resonance of approximately 3 GHz due to the thicker dielectric film. The PVP-based capacitor shows a capacitance at 50 pF for the same plate dimensions with a self resonance of 1.9 GHz which is expected due to the higher capacitance value. The maximum Q for both capacitors seen in Fig. 3(b) is approximately 4. This is due to the thin metal layers and step-discontinuity over the edge of the dielectric and can be improved with more silver layers, or a smoother dielectric edge. Printed inductors in the literature demonstrate a similar Q at this frequency range [9].

As the results from the PVP capacitors provide higher capacitance for a smaller area, further analysis is performed utilizing the PVP ink with varying plate dimensions and number of printed silver layers to test the effect on the capacitance and Q. In Fig. 3(c), PVP capacitors with plate dimensions of 0.5 × 0.5, 1 × 1, and 1.5 × 1.5 mm^2 are plotted against simulation with realized capacitances of 10, 28, and 50 pF, respectively. The measurements agree well with simulation and slight discrepancies are due to small variations in dielectric thickness and mis-alignment between printed layers. The capacitance does not increase



(a) (b) (c) (d)

Fig. 3. Measurement results of (a) SU-8 vs. PVP cap capacitance, (b) SU-8 and PVP cap Q, (c) size versus PVP cap capacitance and (d) PVP capacitor Q.

linearly with plate dimension due to fringing fields at the plate edges. The measured Q for the capacitors ranges from 4 to 8 which is the highest reported Q for printed components in the literature at this frequency range.

To demonstrate the repeatability of the process, three separate capacitors with plate dimensions of 0.5×0.5 mm^2 are shown, with the capacitor designated as Measurement 3 having an extra two printed layers of silver to test the effect of metallization on capacitor Q. As shown, the capacitors designated as Measurement 1 and 2 are in close agreement having capacitances of 10.8 and 10.9 pF respectively. As the two extra printed layers of silver on the third capacitor cause slight spreading making the plates wider, its capacitance is slightly larger at 12.5 pF. However, the Q which is shown in Fig. 3(d) is improved with the extra two silver layers by approximately 20%. The fabrication results demonstrate that the inkjet printed capacitors are highly repeatable within 1% to 2% for capacitance and SRF when utilizing the same process.

IV. CONCLUSION

This article demonstrates the characterization of the printing process for multi-layer, microwave capacitors. Two separate polymer inks are optimized for the Dimatix printing platform. The microwave capacitors produced have values up to 50 pF and self-resonant frequencies of up to 3 GHz allowing for use in the 800 MHz RFID and 2.4 GHz bands. With a smaller capacitance, the SRF can be pushed well above 3 GHz. The repeatability of the process is demonstrated to be within several percent when the same processing conditions are used making it usable in practical system on package, communication, filtering, and sensing applications.

REFERENCES

[1] Y. L. *et al.*, “An all-inkjet printed flexible capacitor for wearable applications,” in *Proc. Symp. Design, Test, Integr. Packag. MEMS/MOEMS (DTIP)*, 2012, pp. 192–195.
[2] S. H. *et al.*, “Fabrication of multilayer passive and active electric components on polymer using inkjet printing and low temperature laser processing,” *Sensors Actuators*, vol. 134, pp. 161–168, 2007.
[3] B. J. Kang, C. K. Lee, and J. H. Oh, “All-inkjet-printed electrical components and circuit fabrication on a plastic substrate,” *Micro- Nano-Eng.*, vol. 97, pp. 251–254, 2012.
[4] R. V. *et al.*, “Paper-based rfid-enabled wireless platforms for sensing applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 57, pp. 1370–1382, 2009.
[5] Su-8 Permanent Photoresists Datasheet [Online]. Available: http://www.microchem.com/pdf/SU-8-table-of-properties.pdf 2013, MicroChem, Tech. Rep.
[6] Y. L. *et al.*, “Preparation of poly(4-hydroxystyrene) based functional block copolymer through living radical polymerization and its nanocomposite with batio3 for dielectric material,” *J. Nanosci. Nanotechnol.*, vol. 9, pp. 7161–7166, 2009.
[7] S. K. *et al.*, “Processing of thin su-8 films,” *J. Micromech. Microeng.*, vol. 18, pp. 1–10, 2008.
[8] B. S. Cook and A. Shamim, “Inkjet printing of novel wideband and high gain antennas on low-cost paper substrate,” *IEEE Trans. Antennas Propag.*, vol. 60, pp. 4148–4156, 2012.
[9] A. M. *et al.*, “Ink-jet printed cpw inductors in flexible technology,” in *Proc. 35th Int. Convention (MIPRO’12)*, 2012, pp. 233–236.