

An Ink-Jet-Deposited Passive Component Process for RFID

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Abstract—An all ink-jet-deposited process capable of creating high-quality passive devices suitable for an RFID front-end is described. Gold nanocrystals are printed to create conductive lines with sheet resistance as low as $23 \text{ m}\Omega$ per square. Optimal printing conditions are found for polyimide dielectric layers and films as thin as 340 nm are produced. These results are used to create spiral inductors, interconnect, and parallel plate capacitors.

Index Terms—Ink-jet printing, passive circuits, printed circuit fabrication, lithography.

I. INTRODUCTION

THE REPLACEMENT of the Universal Product Code (UPC) with radio frequency identification (RFID) tags would allow faster checkout and inventory in retail or supermarket applications. In order to be economically viable, these tags have to be manufactured cheaply, typically for less than one cent per tag. A fabrication method that does not involve expensive processes or the use of silicon substrates is highly desirable. The development of a solution-based process on a flexible substrate would allow reel-to-reel fabrication, which is an extremely inexpensive way to mass-produce circuits since it eliminates conventional lithography, and complex substrate processing including chemical vapor deposition, physical vapor deposition, and etching. While various groups have printed transistors [1], [2] little work has been performed on the associated passives required for RFID. Some work has been done using substrate transfer [3] and evaporated devices [4], but the scalability and manufacturability at low cost is problematic. For the first time an all ink-jet-deposited passive component process is demonstrated on plastic, including inductors, capacitors, and multilevel interconnects. These passive devices are suitable for use in a RFID system operating in the 100 kHz to 15 MHz range. The 13.56 MHz band is ideal for low-cost RFID systems because reader output power is maximized based on FCC specifications, and better range is achieved in metal contaminated environments [5]. The resulting process produces $160 \text{ }\mu\text{m}$ lines with a sheet resistance of $23 \text{ m}\Omega/\square$, and a dielectric capable of providing pinhole-free films as thin as 340 nm or as thick as $3 \text{ }\mu\text{m}$ and above.

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II. BACKGROUND

Passive components such as inductors and capacitors are required in RFID tags because they are used in filters, oscillators, and also for power transfer. Inductive coupling is used to transfer power from a reader to a RFID tag. The tag inductor is placed in the near field of a reader coil, causing a voltage to be induced on the tag inductor. Typically a capacitor is put in parallel with the tag inductor to create a resonant circuit, in order to boost the tag voltage at the tuned frequency [5]. This voltage is then rectified and used as the dc source for any analog or digital processing necessary for communication. High quality components are needed to allow adequate communication range. The main challenge in building high quality inductors is reducing the sheet resistance, because resistance is the dominant loss mechanism at low frequencies. Gold was chosen as a conductor because of its low resistivity and because gold nanocrystals are easily created. Low-temperature solution-processed deposition of gold is achieved by printing gold nanocrystals using an ink-jet printer.

Plastic is a convenient low-cost substrate material that is highly available, nonconductive, and flexible. The best performing substrate with respect to melting temperature and gold adhesion for our purposes was found to be Melinex [6], a polyester made by Dupont Teijin Films. The melting temperature was in excess of $220 \text{ }^\circ\text{C}$, and there was no problem with gold adhesion.

III. EXPERIMENTAL

Gold nanocrystals are made using a wet chemical process, where gold is encapsulated with hexane thiol, resulting in nanocrystals approximately 2 nm in diameter. Due to the extremely large surface area to volume ratio of these particles the melting temperature is approximately $130 \text{ }^\circ\text{C}$, which is significantly lower than the $1000 \text{ }^\circ\text{C}$ bulk melting temperature of gold. This low processing temperature enables the use of plastic substrates that generally cannot tolerate temperatures above $200 \text{ }^\circ\text{C}$ [7], [8]. When deposited onto a heated substrate the solvent evaporates, the thiol encapsulant burns off, and then the gold particles anneal together to form a conductive layer. When combined with an ink-jet printer, nanocrystals are used to create gold patterns on plastic substrates. Minimum feature size is limited only by the size of a drop and the minimum distance the printer is capable of moving.

The printer used to deposit the nanocrystals is a custom drop-on-demand design with a temperature-controlled vacuum chuck so drops may be deposited onto a heated substrate. The ability to jet onto heated substrates is important since it enables

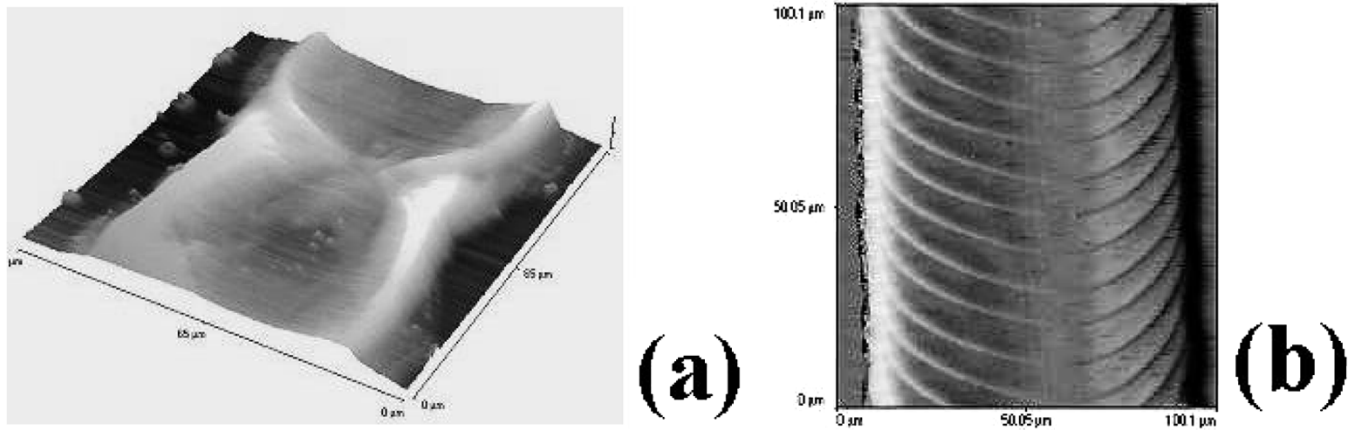


Fig. 1. (a) AFM of line printed with nonlinear method showing extremely rough surface. (b) Line showing linear overlay of drops.

greater flexibility in the control of surface fluid viscosity and evaporation rate. Elevated substrate temperatures reduce the amount printed materials spread after contacting the substrate, and also effects adhesion of some materials such as polyimide. Additional process margin is obtained through careful choice of the solvent used, with particular attention paid to solvent viscosity (to produce stable droplets) and evaporation rate (to minimize in-head clogging). The solvent used, α -terpineol, printed cleanly due to its high viscosity, and also worked well over a heated substrate because of its high boiling point [9]. If a material with low boiling point is used the solvent will evaporate while it is still in the head, leading to a buildup of material and eventually a clogged head. All devices presented in this paper were fabricated using a 60- μm head manufactured by MicroFab Technologies, Inc. [10]. This head has an all-glass delivery path, making it compatible with a wide range of solvents, and uses a piezo-based actuation mechanism that is compatible with the inks and temperatures used herein. Our printer design uses a Teflon reservoir and tubing to enable compatibility with a wide range of organic solvents.

Structures such as inductors and capacitors are constructed by printing a set of lines. There are many ways to create lines from discrete drops, and two methods were investigated for this paper. The first, which turns out to be problematic, places drops only on top of dried nanocrystals (or plastic) and not onto a drop that is still wet. This was an attempt to minimize running of the material by limiting the amount of solvent in a given area. The drops were printed with drop spacings approximately equal to the drop diameter, so that the drops were next to each other, but not touching. Additional layers were then printed on top of the first layer at a small offset, to create thicker lines. Unfortunately the difference in surface tension between the plastic and previous layers of nanocrystals led to an accumulation of material in particular areas, resulting in a very rough line. Fig. 1(a) shows an atomic force microscopy (AFM) image of a line printed using this method. The sheet resistance of this line is dominated by the thin areas, and is significantly worse than that of the purely linear printing method, which is discussed next. This method also printed five times slower because the printer head had to cover a much farther distance, as it was continually backtracking.

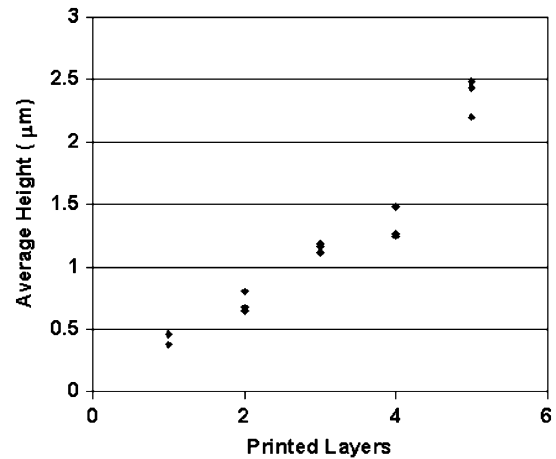


Fig. 2. Average line height plotted versus number of printed layers.

The best way to create lines from drops is to overlay them in a linear fashion. Drops are deposited using 5- to 15- μm spacing, resulting in 8 to 24 layers of drops at any given point on the line. Fig. 1(b) shows an example of how the drops are overlaid. This method gives lines with uniform distribution of nanocrystals in the printed direction. The cross section, however, is not uniform. This is due to the fact that printed drops tend to have a ‘donut’ shape with more material around the edges than in the center. This effect was minimized through the use of solvents such as α -terpineol and by heating the substrate [11].

IV. RESULTS AND OPTIMIZATION

A. Low-Resistance Gold Lines

In order to create thicker lines and reduce sheet resistance, multiple passes are made with the print head and lines are placed directly on top of each other. As the number of layers is increased there is a linear increase in the average line height shown by Fig. 2. There is a slight increase in line width up to about three layers due to different surface tensions between the gold and plastic surfaces. However, after about three layers the line width stabilizes at 160 μm , which allows the optimization of structures such as inductors, where the lines need to be placed as close as possible.

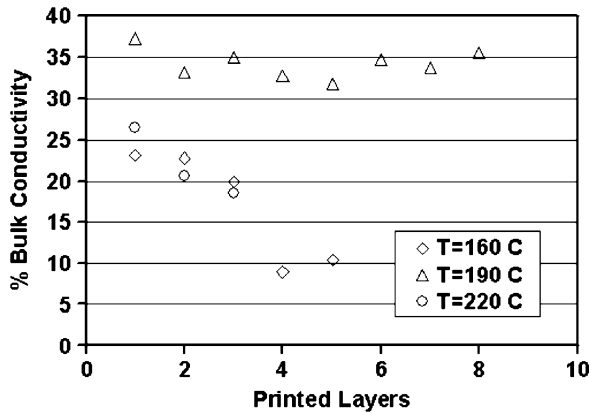


Fig. 3. Quality of printed gold as a function of bulk conductivity showing no degradation at 190 °C as the number of layers increases.

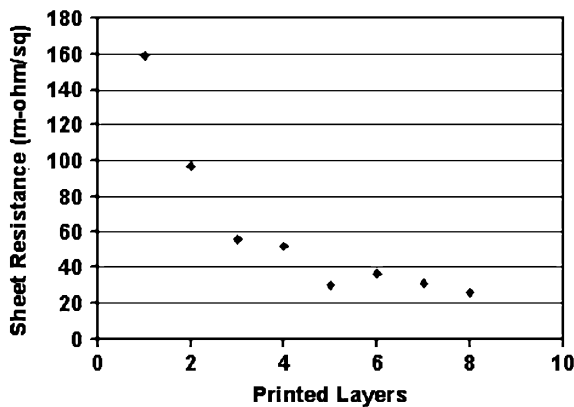


Fig. 4. Inverse relationship between sheet resistance and number of printed layers at 190 °C.

Printing at elevated temperature helps reduce the “donut” effect on the drops so lines are typically printed at 160 °C to 190 °C. The substrate temperature has a significant influence on the quality of the printed gold, which is measured as a percentage of bulk conductivity. Three different substrate temperatures were tested: 160 °C, 190 °C, and 220 °C, and the resulting conductivity of the gold was measured versus the number of printed layers. Results as high as 4% of the bulk conductivity were achieved.

As Fig. 3 shows, there is a decrease in the quality of the gold as the number of printed layers is increased at temperatures of 160 °C and 220 °C. For those temperatures printing extra layers of gold does not improve the sheet resistance as much as expected. At 190 °C there was no decrease, so this temperature was chosen for printing. At 160 °C the additional layers may have been put down too quickly, not allowing thiol from previous layers to burn off completely. The thiol cannot diffuse through the upper layers and becomes trapped. This is supported by another experiment using toluene as the solvent. In that case, the amount of gold printed was significantly less, and the lines were much thinner, therefore allowing more thiol to escape. Conductivities as high as 70% of bulk gold were achieved in that case, but the sheet resistance was unacceptable due to the thinness of the lines. An explanation has not been found for the decreased gold quality at 220 °C.

The sheet resistance was measured versus number of printed layers at 190 °C. Fig. 4 shows the inverse relationship between

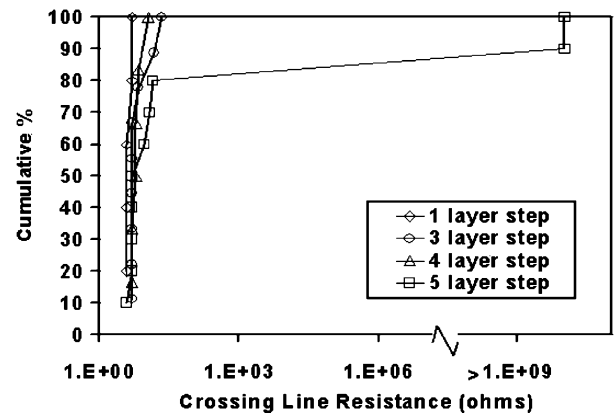


Fig. 5. Good step coverage is achieved for gold lines up to 2.5 μm thick. Crossing line resistance represents the resistance of a line passing over another insulated line. High crossing line resistance indicates an open.

number of layers and sheet resistance. Resistance as low as 23 $\text{m}\Omega/\square$ was achieved.

B. Crossovers and Interconnect

Pinhole-free films are necessary for the creation of capacitors, center taps for inductors, and interconnect. PI2555 polyimide from HD Microsystems, Inc. was used as the dielectric. The polyimide was diluted 2:1 with Pyralin thinner from the same manufacturer.

Polyimide is extremely sensitive to substrate temperature. Pinhole-free films require the correct substrate temperature and the correct drop spacing. If too much material is deposited the polyimide agglomerates and does not form a film. Temperature was varied from 50 °C to 110 °C and drop spacing was varied from 50–90 μm in the x and y directions. Drops were printed every 175 ms. Rectangular pads of polyimide were created using a linear array of lines, adjusting the line spacing to equal the drop spacing. The best conditions were found using a substrate temperature of 90 °C with drop and line spacing of 60 μm . The surface of this film is quite rough; with an average thickness of 1 μm .

These films are used as an insulating layer allowing the creation of multilayer interconnect. The crossing line resistance, shown in Fig. 5, tests the step coverage of the top gold line. The layers in the figure represent the number of printed layers of gold in the bottom conductor. Good step coverage is achieved for gold lines up to 2.5 μm thick. Fig. 6 shows the insulating properties of the dielectric versus number of printed layers. Three layers of dielectric are needed to ensure isolation, which results in an average film thickness of 3 μm .

C. Inductors

Spiral inductors of 350 nH were fabricated using three layers of printed gold. Since the ink-jet printer is not limited to Manhattan designs, spiral inductors were fabricated rather than square inductors. Spiral inductors are superior to square inductors because they give higher quality factors for a given inductance. These structures were created in a piecewise-linear manner with 32 segments. The measured inductance agreed extremely well with simulation using ASITIC [12]. The inductors had radii of 5000 μm , line widths of 160 μm , line spacing of

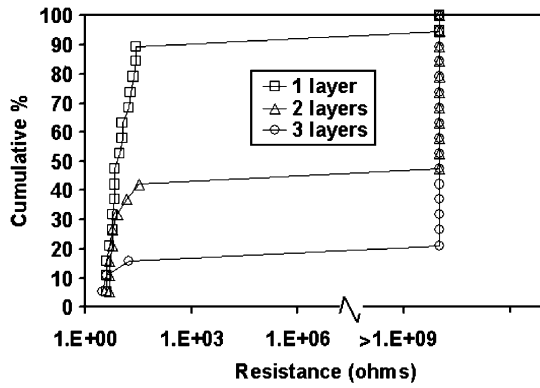


Fig. 6. Three layers of polyimide provides adequate isolation. The resistance measured is between the top and bottom conductors. High resistance indicates an open circuit and therefore good isolation.

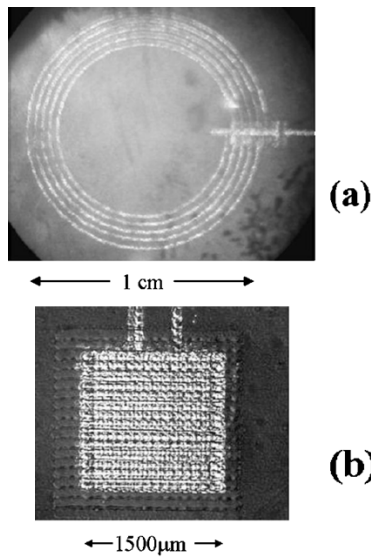


Fig. 7. (a) A 350-nH inductor complete with contact to center coil achieved using the crossover process. (b) All printed capacitor.

100 μm , and five turns. Center taps were achieved using three layers of printed polyimide as an insulator, and then printing a line from the innermost turn across the device to the outside where connections to other devices can be made.

Fig. 7(a) is a picture showing one of these devices. Resistance is the major loss mechanism for these inductors. The series resistance was approximately 58Ω , giving a quality factor (Q) of 0.5 at 13.5 MHz. This value is too low for use in RFID circuits, but additional layers of gold would improve the quality factor of this device to approximately unity. This inductor geometry is also not optimal for the given inductance value. An optimized structure would use additional turns to fill more area in the center of the inductor. Using a sheet resistance of $23 \text{ m}\Omega/\square$, simulations were run using ASITIC to determine the highest achievable Q for a $1 \mu\text{H}$ spiral inductor using this process. Inductor radius was varied and the number of turns was adjusted to give the correct inductance, and then Q was calculated at 13.5 MHz. Line widths were kept at a constant 160 μm , and line spacing was fixed at 50 μm . Quality factors of 2.5 are obtainable for $1 \mu\text{H}$ inductors. As Fig. 8(a) shows, the radius of the inductor does not have a large effect on the inductor quality. Hence inductors should be

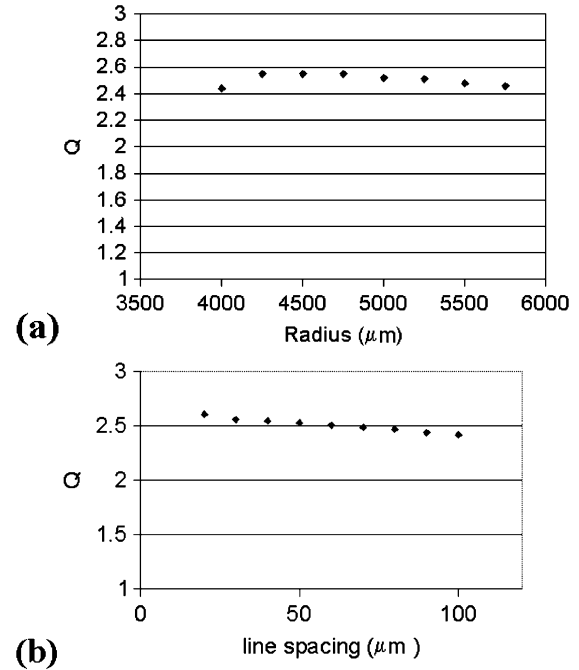


Fig. 8. (a) Simulated results showing variation of Q with inductor radius at 13.5 MHz. Realizable quality factor is fairly independent of inductor radius. (b) Quality factor decreases slightly as line spacing is increased.

made as large as possible to maximize the coupling factor between reader and tag inductors. Further simulations indicated that a larger line width would increase the Q to 5, for inductors of the same value. It would be possible to print wider lines by essentially printing two inductors at the same origin, one with a slightly larger radius.

Variation of the line spacing was also investigated. Using smaller line spacing increases the inductance per length of printed lines. However, the gain in Q as line spacing is reduced from 100 to 20 μm is fairly small at 10%. Fig. 8(b) shows the variation of Q versus line spacing for $1 \mu\text{H}$ devices with fixed radius of 5000 μm . Larger inductors generally give higher quality factors. The highest simulated Q (at 13.5 MHz) was 9.5 for a large inductor with 15 000- μm radius, 300- μm line width, 20- μm line spacing, and 20 turns. The inductance was $12.7 \mu\text{H}$, which is reasonable for this application.

This process can also be used to create much smaller inductors of a few nanohenries, which could be used in high-frequency filters in the GHz range. Due to the smaller inductance, fewer turns are needed and resistive loss would no longer dominate the quality factor. Accounting for resistance only, a Q of 20 would be possible at 1 GHz. Plastic substrates are superior to silicon in the sense that they are nonconductive, which will limit the effect of other loss mechanisms such as eddy currents. ASITIC electromagnetic simulations give a quality factor of 12 at 1 GHz for 1.5-turn spiral inductors with 1000- μm radius.

D. Capacitors

Parallel plate capacitors were fabricated by first printing a bottom plate, then printing three layers of polyimide, and then printing a top contact. The dielectric must be as thin as possible to create capacitors large enough for use at 13.5 MHz. In order

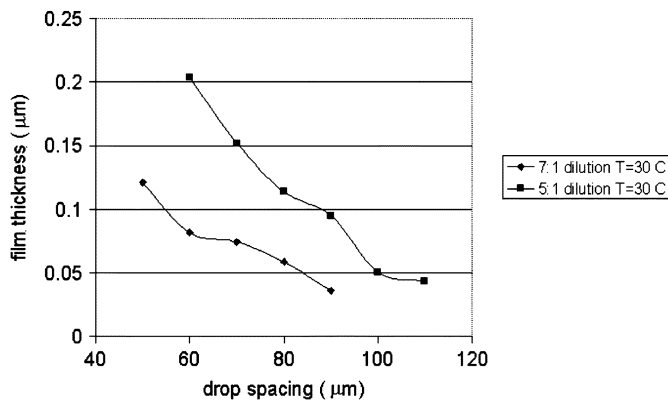


Fig. 9. Effect of drop spacing on polyimide film thickness at 30 °C.

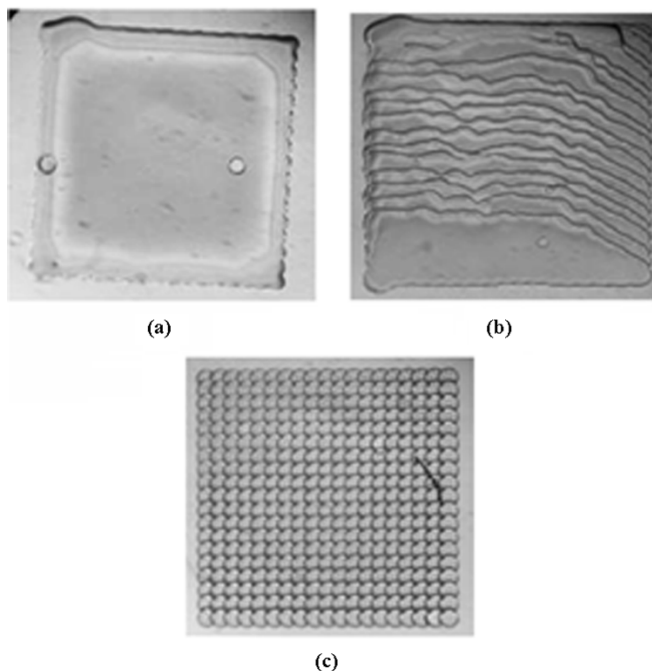


Fig. 10. (a) Effect of substrate temperature on polyimide surface using 80-μm drop spacing at 30 °C, (b) 60 °C, and (c) 110 °C.

to get thin dielectric films that provided good isolation the gold bottom plates had to be smooth. Rough bottom plates with a thin insulating layer results in shorted capacitors. Gold was deposited at 45 °C so that the material is allowed to flow on the surface without drying too quickly. Once a smooth gold layer was deposited and annealed a thin layer of polyimide was printed. The polyimide was diluted using the same thinner as before to 3:1, 5:1, and 7:1, and a drop spacing and temperature matrix was run to determine optimal printing conditions. Temperatures of 30–110 °C were tested with drop spacings of 50–120 μm in the x and y directions. Film thickness was as low as 35 nm. Substrate temperatures of 60 °C and higher resulted in films that were extremely rough because the lines dried before the next line was printed. The surface roughness disappeared at temperatures below 60 °C, allowing the material to remain liquid as the adjacent row of drops was printed. Temperatures of 30 and 45 °C gave smooth films. Fig. 9 shows the effect of dilution and drop spacing on film thickness. Photos of films printed at 30, 60, and 110 °C are shown in Fig. 10. At elevated temperatures

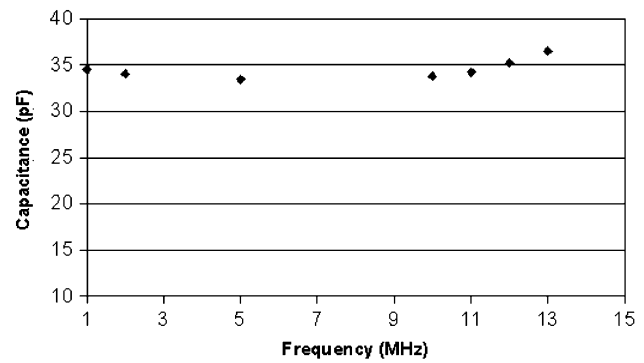


Fig. 11. Dispersion characteristics of printed capacitors. Note that the upturn at high frequency is within the error bars of the measurement.

the polyimide will dry in lines, and then eventually individual drops can be seen. The delay between printing each drop was approximately 25 ms.

Capacitors were fabricated using the smooth gold pads and thin dielectric. Polyimide diluted to 7:1 was deposited at 45 °C using drop spacings of 70 μm. In order to ensure isolation between capacitor plates three layers of polyimide were used, even though this decreased the capacitance. Capacitors fabricated with three layers of polyimide proved to be the most reliable, with high yield. The resulting 600 × 600 μm capacitors had an average capacitance of 42 pF. Fig. 7(b) shows an all-printed capacitor fabricated using this process. The film thickness is approximately 340 nm, allowing the fabrication of capacitors suitable for use in RFID applications. All devices tested had a breakdown voltage greater than 70 V. The dispersion characteristics of the capacitors were measured to see if there was a degradation of the dielectric at higher frequencies. Capacitance was measured as the frequency was swept from 1 to 13 MHz. Fig. 11 shows that polyimide is a viable dielectric material for low-frequency RFID applications. The relative permittivity was calculated to be 4.5, which is slightly higher than the manufacturer's value of 3.3 [13]. This is due to surface roughness of the capacitor plates, and thickness variation inherent in printing.

V. DISCUSSION

This all-ink-jet-deposited process is capable of producing inductors and capacitors suitable for use in the front-end of an RFID tag. Optimization of the inductor structure is necessary to achieve quality factors suitable for data and power transfer. Large inductors with wider line widths achieved the highest quality factors. For a given inductance radius and line spacing did not have a major effect on quality factor, so there is not a large penalty for using large radii to increase coupling from reader to tag or using a large line spacing to increase inductor yield. Using the average measured capacitance value of 42 pF the required inductance to achieve resonance at 13.5 MHz is 13 μH, which can be fabricated with a quality factor of 9.5. Such a system would have the range and bandwidth required for an electronic replacement of the UPC barcode, allowing on-shelf inventory and rapid checkout.

In order to further improve sheet resistance and reduce cost, silver and copper nanocrystals have been developed. Although

gold is a fairly expensive material, cost models indicate that throughput will dominate over other costs in the manufacture of RFID tags. Moving to a different metal would decrease cost slightly, but the main advantage is that silver and copper both have bulk conductivities that are approximately 50% higher than gold. These materials are currently being tested to see if the nanocrystals behave in a manner similar to gold, and conductivities of 40% of bulk can be achieved. The improved conductance would further increase system range.

Other potential applications exist for this technology. Small high- Q inductors (3 nH) can be fabricated for use in high frequency filters, but polyimide may not be suitable for use as a dielectric at gigahertz frequencies. However, there are materials known to function at these frequencies such as benzocyclobutene (BCB), which could be printed. This would allow the fabrication of discrete filters at gigahertz frequencies. Distributed filters on BCB substrate would also be possible.

VI. CONCLUSION

A low-cost method of fabricating passive devices on plastic substrates has been developed. These passives are suited for use in low-frequency RFID applications. The gold nanocrystal process has been extensively characterized, and gives consistent results. Polyimide has been shown to be an effective dielectric for isolation, and its dielectric constant does not change significantly at the frequencies of interest, making it suitable as a capacitor dielectric.

This paper represents a first step in developing a low-cost all-printed RFID system. Future steps include the development of an active device technology, and investigating circuit architectures suited for use with low-performance active devices.

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