Fabrication and characterization of CNT inductors on flexible plastic substrates

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Abstract

A scalable and compact inductor is one of the critical components for passive radio-frequency (RF) devices and sensors. All-organic passive sensors have unique applications. RF sensors made of carbon nanotube (CNT) films on flexible substrates made of materials such as polyethylene terephthalate (PET) and Kapton® could be used to measure temperature, pressure, and strain. CNT thin films have high yield strength and flexibility at high temperatures. In this paper, we report the fabrication and characterization of CNT inductors on flexible plastic substrates. The performance of CNT inductors is compared with those made of printed silver nanoparticles. The surface roughness of CNT films was measured by laser confocal microscope, and the CNT morphology was studied by scanning electron microscope. Electrical resistance plays an important role in inductor performance. The sheet resistance of our inductor made of printed nanoparticles and SWCNTs could reach 0.5 ohm/sq and less than 3 ohm/sq, respectively. The resonant peaks of the fabricated inductor fall into the range of 10-200 MHz. The fabricated inductors were characterized by a network analyzer. The effect of temperature on inductor coil performance is discussed.

Key words: carbon nanotubes, inductors, resonant frequency, printed electronics, flexible substrate.

1. INTRODUCTION

Carbon nanotubes (CNTs) are emerging electronics materials with fascinating properties. It has been experimentally verified that "metallic" CNT zigzag nanotubes actually have energy gaps, and bundled armchair nanotubes have pseudo–energy gaps [1]. In theory, the electronic properties of metallic and semiconducting CNTs are solely determined by the diameter and chirality of the "ideal" CNTs. However, it was later found that defects in CNTs could dramatically modify their electronic properties at individual CNT length scale. Simulation showed the performance of nanoscale electronic devices can be improved by modifying the density of states of the tube at the individual CNT-scale length by introducing defects such as capping of tube ends, intra-tube junctions, and irradiation of tube walls [2]. The effect on bulk-scale discrete electronic devices such as inductor coils, capacitor electrodes, and conductive traces is yet to be seen, but it looks promising.

Using a CNT inductor for making inductor coils was investigated due to its high current-carrying density, long electron mean free path, and high thermal conductivity in the CNTs, as shown in Table 1.

Few reports [3,4,5] of simulated CNT inductor performance are in the literature, but there is no explicit report of a functional CNT inductor in terms of reflection (transmission)/phase characteristics in the operating frequency range of 10-200 MHz or higher. One of the issues for CNT inductor coils was their high resistivity, and researchers attempted to make CNT inductors operating in the GHz range [6] using e-beam lithography, as the required total length of the CNT inductor coils is short and the total resistance is acceptable.

Table 1. Properties of CNTs compared to those of copper [7-13]. CNTs are either single-walled (SWCNTs) or multiwalled (MWCNTs).

	Maximum current density (A/cm^2)	Mean free path (nm) at 25 °C	Thermal conductivity (× 10^3 W/m-k)
SWCNT	10^9	10^3	1.7-5
MWCNT	10^9	10^4	3
Cu	10^7	40	0.385

In this paper, we will report progress made in fabrication of CNT and silver inductor coils in the frequency range of 10-200 MHz and the characterization results.

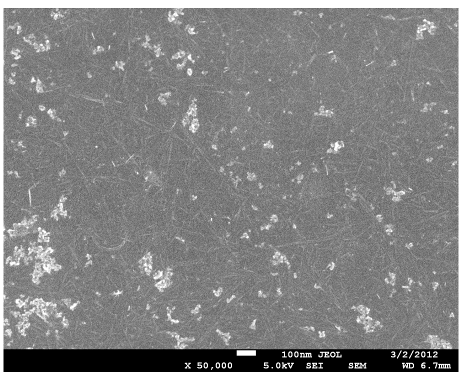
2. FABRICATION OF SILVER AND CNT INDUCTOR COILS

To understand the characteristics of CNT inductor coils, a silver nanoparticle inductor was printed on polyethylene terephthalate (PET) by Uni-Jet. The platen temperature was set at 60°C during deposition, and then the film was cured at 130°C for 30 minutes. The outer diameter and width of the 6-turn square inductor coils were 40 mm and 1.46 mm, respectively. Total resistance of the square silver nanoparticle inductor coil was 50 Ω.

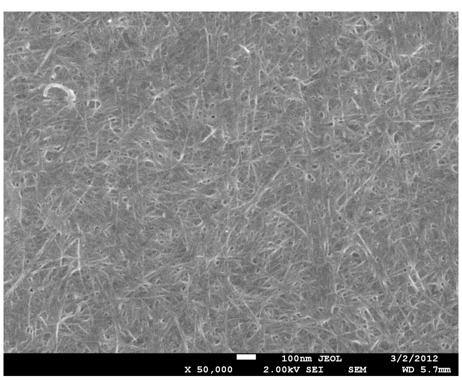
CNT thin films can be deposited by spray coating, ink-jet printing, and screen printing. Our inductor coils were deposited on PET by a spray coater made in-house.

The platen was heated up to 130°C, and no post-deposition processing was necessary. The outer diameter and width of the 5-turn circular inductor coil were 20 mm and 0.9 mm, respectively. The total resistance of the circular CNT inductor coil was 166 Ω.

Depending on deposition parameters and the ink concentration of the CNT solution, the film thickness varies. To estimate the CNT film thickness and surface roughness on PET, the CNT film was deposited on a glass slide, and the film was analyzed with a laser confocal microscope. The measured 1-pass CNT thin film thickness here was 1218 nm with a surface roughness of 232 nm. The CNT films were also characterized by a scanning electron microscope. An 8-pass SWCNT thin film on a glass slide is shown in Figure 1(a), and an 8-pass double-walled CNT thin film on a glass slide is shown in Figure 1(b). It can be seen from the SEM images that both SWCNTs and MWCNTs were bundled.



(a)



(b)

Figure 1. (a) SEM image of 8-pass SWCNT thin film and (b) SEM image of 8-pass double-walled CNT thin film.

3. CHARACTERIZATION OF INDUCTOR COILS

The silver inductor and CNT inductor coils were characterized by a network analyzer, and the expected resistance performance of such inductor coils at high temperature is discussed below.

3.1 Experimental Setups

The reflection frequency responses of inductor coils were characterized by an Agilent network analyzer with a transmission/reflection test kit. The inductor coils were wired on a prototype board as illustrated in Figure 2. The circuit board was connected to the test kit by RF connectors.

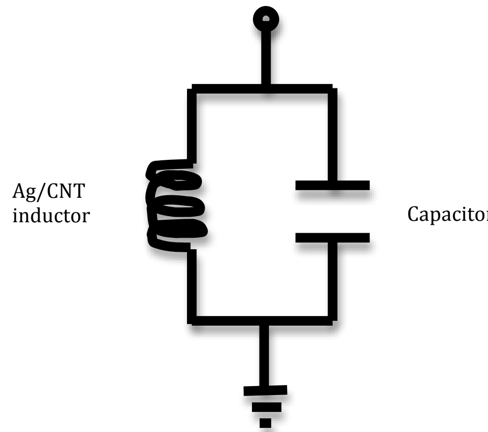


Figure 2. Illustration of inductor and capacitor wiring diagram on the prototype board.

3.2 Reflection Response of Silver Inductor Coil

For the silver inductor coil, there was a reflection peak at 23 MHz (Figure 3). This peak results from the parallel resonance of the inductor and the 47-pF commercial off-the-shelf (COTS) capacitor. The reflection minimum at higher frequency suggests that a parasitic series resonance exists in the circuit.

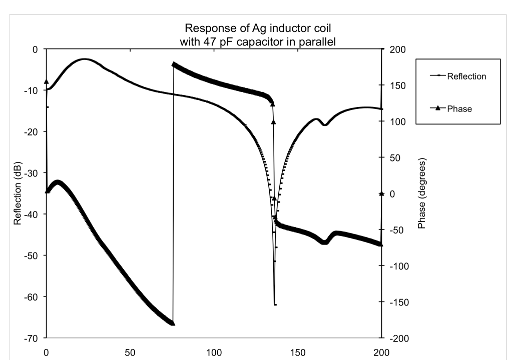


Figure 3. Reflection and phase plot of silver inductor coil in parallel with a COTS capacitor.

3.3 Reflection Response of CNT Inductor Coil

As shown in Figure 4, for the CNT inductor coil, there was a reflection peak at 117 MHz. This peak resulted from the parallel resonance of the CNT inductor and the COTS 4.7-pF capacitor. The parasitic series resonance in the CNT circuit was identified at a frequency that is lower than the parallel resonance frequency.

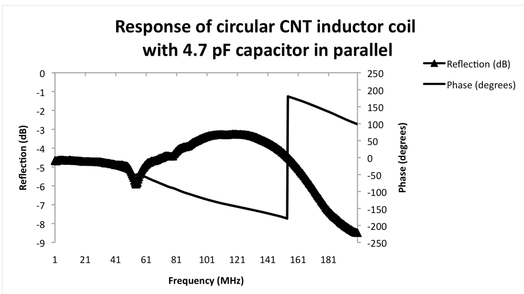


Figure 4. Reflection and phase plot of CNT inductor coil in parallel with a COTS capacitor.

3.4 Performance of Inductor Coils at High Temperature

As the temperature is increased, the reflection peak frequency and amplitude of the circuit is expected to change. If the inductor is designed to function as an antenna or an RFID element, it is desired to have a stable resonance frequency; if the inductor is configured to function as a sensing element, it is desired to have a tunable resonant peak. The exact mechanism of such frequency shift is not understood completely. It is expected that the resistance of the inductor coils, the capacitance, and the inductance are going to change at elevated temperatures at the same time. The capacitance and inductance changes caused by change in temperature are beyond the scope of this paper. Here we will discuss the resistance change due to increase in temperature.

The temperature dependence of the resistance of individual metallic SWCNTs was measured in an ultrahigh vacuum (UHV) environment in the range of 300-1200K [14]. It was found that the electron-phonon coupling is relatively weak in this range. In the range of 300K-900K, the resistance was linear with an average thermal coefficient of resistance of 0.0014 K^{-1}, approximately three times smaller than the same coefficient for a bulk metal.

The generally accepted model [15] of resistance of a CNT is

$$R = R_c + R_o\left(1 + \frac{L}{\lambda_{MFP}}\right),$$

where R_c is contact resistance, R_o is minimum resistance, L is the length of the tube, and λ_{MFP} is the electron mean free path due to electron-phonon coupling effect.

For bulk CNT films, the situation is more complicated. However, it is generally accepted that it scales with a similar pattern in a certain temperature range. The behavior of the silver inductor coil and CNT inductor at elevated temperature will be studied and will be reported elsewhere.

4. CONCLUSIONS

In this paper, we reported the fabrication and characterization of functional CNT inductors on flexible plastic substrates. The sheet resistance of our CNT films reached less than 3 ohm/sq. Surface roughness of CNT films was measured by laser confocal microscope, and the CNT morphology was studied by scanning electron microscope. The reflection responses of the CNT inductors were compared with those made of silver nanoparticles. The parallel and series resonance peaks were identified on a network analyzer in the range of 10-200 MHz. The performance of inductor coils at elevated temperatures was discussed. The performance of CNT inductance is going to be much more stable than that of silver nanoparticles.

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