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Carbon nanotubes as base material for fabrication of gap waveguide components

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Abstract

Carbon nanotubes are being used here as a base material for rapid prototyping of a high frequency device. It has been implemented on a ridge gap resonator for 220-325 GHz which has previously been fabricated in Si. Microfabrication with Si has its benefits but it is time consuming when etching high ratio structures. CNT based structures offer a rapid and low cost turnover for prototyping. Measurements comparing the CNT-based structure to a previously made Si structure and simulations are presented. The unloaded Q-values and the loss/mm are presented from simulations, Si-based resonator measurements and CNT-based resonator measurements.

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Keywords: GHz, High-frequency, MEMS, RF, Metamaterial, Gap Waveguide, Carbon nanotubes.

1. Introduction

In the field of MEMS, rapid prototyping with a low cost can give a huge advantage. By using carbon nanotubes (CNT) for RF MEMS applications, there can be fast and low-cost turnover for fabrication of prototypes. Gap waveguide devices for above 100 GHz such as the ridge gap resonator for 220-325 GHz [1] and the 100 GHz groove and ridge gap waveguides [2, 3] have been micromachined in Si. However this is a time consuming and costly process. Previously a ridge gap resonator has been fabricated out of SU8 [4], this design was based on the ridge gap resonator presented in [1], which was fabricated for the frequency range of 220-325 GHz. SU8 is a low-cost material

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compared to Si but equally time consuming [4]. Therefore there is an interest to explore faster and cheaper processes for rapid prototyping of high frequency devices. In this paper a ridge gap resonator operating at 220-325 GHz based on a previous device made out of Si [1] has been fabricated with a gold covered carbon nanotube base.

The basic principle of the resonator is based on the combination of a Perfectly Electrically Conducting (PEC) surface and an Artificial Magnetically Conducting (AMC) surface parallel to each other. These two surfaces will create a stopband between them [5]. When embedding a PEC ridge into the AMC surface, it allows the wave to propagate along the ridge between the two PEC surfaces (Fig. 1). The AMC is obtained by a metamaterial surface known as "bed of nails" [6].

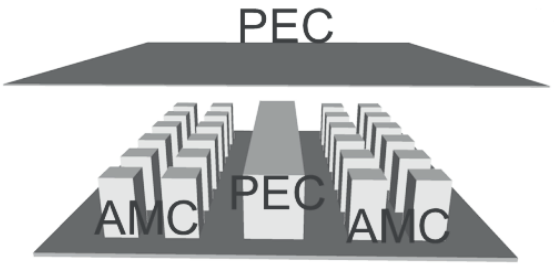

Fig. 1. Schematic view of the principle of a ridge gap waveguide. The ridge and the lid are PEC surfaces and the pin surface area acts as AMC surfaces.

2. Design

The CNT-based ridge gap resonator has the same structure and design as the Si-based ridge gap resonator, [1]. However here the pins and the ridge are gold covered bundles of CNTs but the carrier layer is still Si. The pin width is 167 μm and the intended pin height is 277 μm. The ridge has two pin-rows along the sides and one pin row at the connecting sides where the measurement flanges will be connected, Fig. 2.

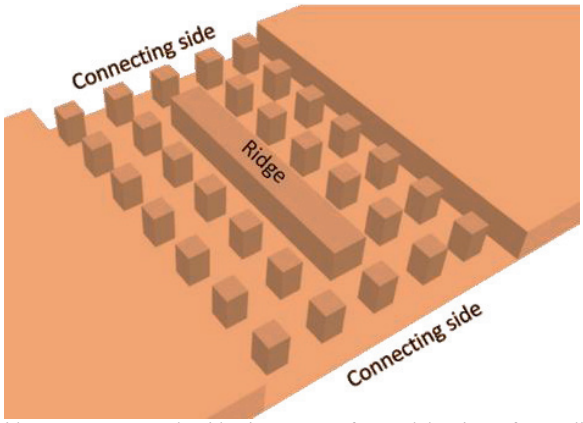

Fig. 2 A schematic 3D image of the ridge gap resonator. The ridge is a PEC surface and the pin-surface realizes the AMC surface. The pin height is 277 μm and the gap height is 167 μm.

3. Fabrication

Thermal Chemical Vapor Deposition (CVD) is the most feasible technique to grow bundles of vertically aligned carbon nanotubes on silicon substrate. It is quicker and cheaper than ICP DRIE technique where pins are made by etching Si. It uses low cost gases and can grow up to 1 mm long bundles of vertically aligned carbon nanotubes in a few minutes. The catalyst is required to grow the carbon nanotubes on silicon substrate. The negative resist

lithography and lift-off technique is used to obtain the catalyst. The schematic diagram of the fabrication process is shown in Fig. 3.

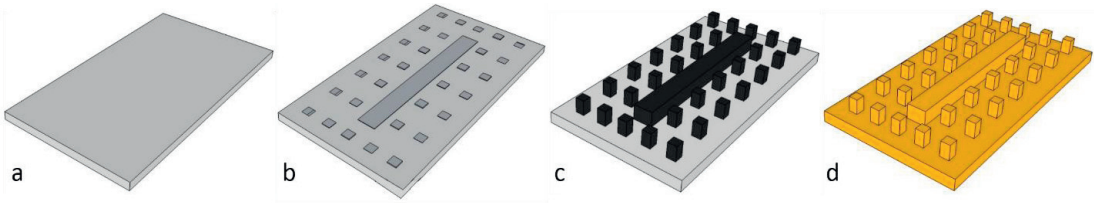

Fig 3. Process plan of the resonator. a) 2 inch silicon wafer of thickness around 260 µm. b) Definition of catalyst using lithography. c) Growth of carbon nanotubes using thermal CVD. d) Deposition of aluminum/titanium/gold conductive seed layer

A 2-inch Si wafer with a thickness 260 µm was used to get the optimum thickness of CNTs and substrate assembly to fit in to measurement setup, Fig. 3a. First a layer of Primer HMDS was spun and then AZ5214 negative photo resist was spun. After lithography 5 nm Al was evaporated and then 2 nm Fe was evaporated in the same run using an electron beam evaporation machine (**Evaporator Lesker**) followed by lift-off in 1165 remover, IPA and water rinse, Fig. 3b. The bundles of vertically aligned carbon nanotubes were grown using thermal chemical vapour deposition in AIXTRON NanoInstruments Black Magic, Fig. 3c. First the catalyst was pre-treated at 500 ˚C temperature for 3 minutes in the environment of continuous flow of hydrogen gas at around 8 mbar pressure then the temperature was raised to 700 ˚C within a few seconds and acetylene gas was introduced in the chamber. Here, the hydrogen was used as a carrier gas and acetylene was used as source gas. The growth was carried out for 7 minutes 30 seconds to get the 290 µm long bundles of vertically aligned carbon nanotubes. After growth 1 µm Al, 20 nm Ti and 100 nm Au were sputtered in the same run using FHR MS150 machine. These metals layers were sputtered sequentially to fill the gap between carbon nanotubes and to provide conductive top surface, Fig 3d. The thickness of Al metal layer was five times the skin depth of the chosen frequency band.

4. Results & Conclusion

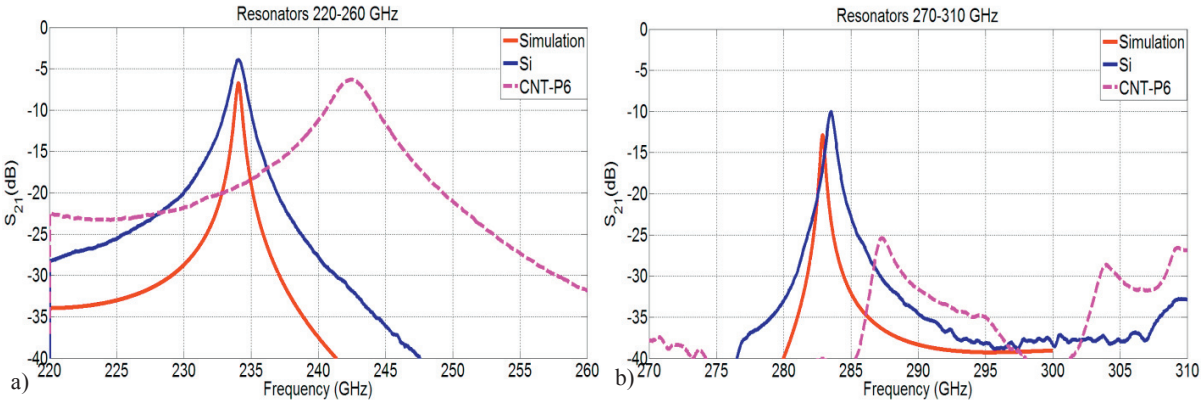

Fig. 4. Comparison between the measurements of the Si and CNT resonator and simulations at a) 220-260 GHz, b) 270-325 GHz.

The first CNT-based ridge gap resonator with an unintended height of 290 µm was measured and compared to measurements for the Si-based resonator and to simulations. The measurements were divided into two frequency ranges, 220-260 GHz and 270-325 GHz to have a high number of measurement points. The measurements can be seen in Fig. 4a and 4b. Table 1 shows the unloaded Q-values and the loss/mm extracted from the resonance peaks. The CNT-based resonator shows resonance within the two frequency ranges, which indicates that the CNTs works

as a base material. However the peaks are shifted and their respective Q-values are lower compared to the Si-based resonator and simulations. This is probably due to the unintended, too high pin height. A new optimized CNT-based resonator with a pin height of 278 μm (Fig. 5) has been fabricated. Measurements are intended to be presented at the conference.

Table 1. Measured and simulated unloaded Q-values and loss/mm.

	Simulation		Si		CNT	
Frequency	234.1 GHz	282.9 GHz	234.1 GHz	283.5 GHz	242.4 GHz	287.3 GHz
Qu-value	867	915	581	590	257	213
Loss dB/mm	0.025	0.028	0.033	0.044	0.08	0.123

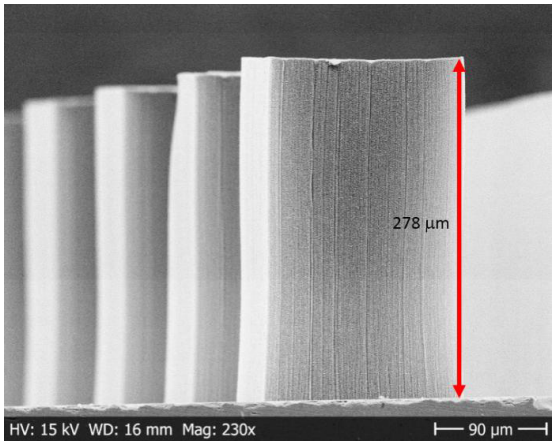

Fig 5. SEM image of a CNT-based pin with a height of 278 μm.

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