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Carbon nanotubes as base material for fabrication of gap waveguide components☆

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ABSTRACT

Microfabrication with Si has its benefits but it is time consuming when etching high ratio structures. Previously a ridge gap resonator has been fabricated in Si, with a pin height of 278 μm. In this paper carbon nanotubes, which can grow hundreds of micrometers within minutes are being used as a base material for a high frequency device. It has been implemented on a ridge gap resonator for 220–325 GHz. Carbon nanotubes based structures offer a rapid and low-cost turnover for prototyping. Measurements comparing two carbon nanotubes-based structures to a previously made Si structure and simulations are presented. From these measurements the unloaded *Q*-value and the loss/mm have been calculated and shows a loss of 0.079 dB/mm and 0.051 dB/mm for the lower frequency range respectively the higher frequency range, indicating that carbon nanotubes can be used for fast and low-cost prototyping of high-frequency devices.

1. Introduction

In the field of MEMS, a rapid low cost prototyping can give a huge advantage. By using carbon nanotubes (CNTs) for RF MEMS applications, there can be fast and cheap turnover for fabrication of prototypes.

The CNTs are allotropic forms of carbon discovered by Iijima in 1991 [1] and since then they have received high attention due to their extraordinary electrical, thermal and mechanical properties such as the thermal conductivity along the axis (about 3500 W m K^{-1} at room temperature) is eight times higher than copper [2] and they also have the ability to carry electric current density three times more than copper [3]. They are very strong mechanically having a high Young's moduli and tensile strength of 1 TPa and 63 GPa respectively, both are many times higher than steel [4]. The CNTs are generated by seamlessly rolling up a graphene sheet into a cylinder and can be single-wall or multi-wall depending on if one or multiple sheets are rolled up coaxially. In addition, the single-wall CNTs (SWCNTs) can be metallic or semiconducting depending on the twist of the tubes, however 2/3 of the CNTs are known to be semiconducting when grown in bulk [5].

Previously, gap waveguide devices for frequencies above 100 GHz such as the ridge gap resonator for 220–325 GHz [6], the groove and ridge gap waveguides for 100 GHz [7,8] have been micromachined in Si. However this is a time consuming and costly process.

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 when they are closer than quarter of the wavelength [9], and 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 surface is obtained by a metamaterial surface known as "bed of nails" where the pins or "nails" needs a minimum length of 277 μm [10]. Resonators are used to determine the loss per mm of the device [11].

Previously a ridge gap resonator has been fabricated out of SU8 [12], this design was based on the ridge gap resonator presented in [6], which was fabricated for the frequency range of 220–325 GHz. SU8 is a cheaper material than silicon but equally time consuming in fabrication. The fabrication time of ridge gap resonator from CNTs takes less than 2 h whereas 5 h from SU8, estimated from the process presented in [12].

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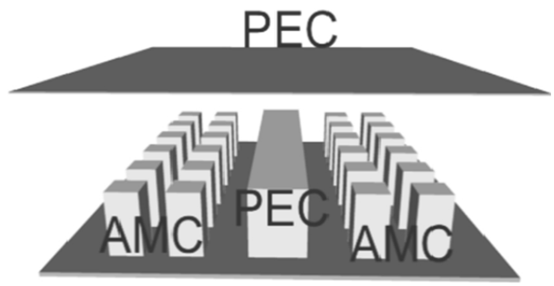

Fig. 1. Schematic view of the principle of a ridge gap waveguide. The ridge and the lid are PEC surfaces and the pin surface area acts as AMC surfaces.

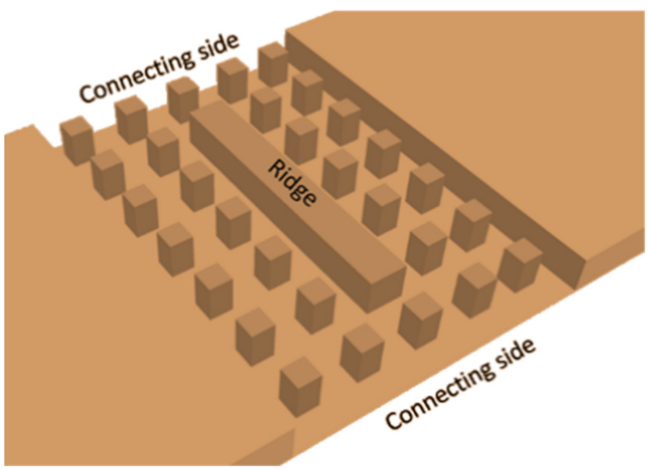

Fig. 2. A schematic 3D image of the ridge gap resonator. Design of a ridge gap waveguide. The ridge is a PEC surface and the pin-surface realizes the AMC surface. The pin height is 277 μm and the gap height is 167 μm.

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 frequency range has been fabricated with the gold covered CNTs as base. The CNTs grow up to 50 times faster than an ICP DRIE process which can etch the same structures in silicon. By utilizing the CNTs as a base material, fast and cheap prototyping of high frequency RF devices can be done.

2. Design

The CNT-based ridge gap resonator has the same structure and design as the silicon-based ridge gap resonator [6]. However here the pins and the ridge are gold covered forests of the CNTs but the carrier layer is still silicon. The pin width is 167 μm and the intended pin height is minimum 277 μm. The ridge has two pin rows along it and one pin row at the connecting sides where the measurement flanges will be connected, Fig. 2. The PEC lid is placed 167 μm above the ridge.

3. Fabrication

Conventional inductive coupled plasma (ICP) deep reactive-ion etching (DRIE) technique with the STS ICP dry etching machine is used to etch high aspect ratio structures, but has an etch rate of 2–3 μm/min, which is time consuming when etching hundreds of micrometers. Thermal chemical vapor deposition (CVD) can grow high aspect ratio CNT bundles within minutes and at a low-cost. This is due to that it uses low cost gases and is fast as it can grow up to 1 mm long bundles of vertically aligned CNTs in a few minutes thus short machine time and small amount of gases are needed. A catalyst is needed to grow the CNTs on silicon substrate and lift-off technique is used to pattern the catalyst. The schematic diagram of the fabrication process is shown in Fig. 3.

Instead of using a top-down approach, a bottom-up approach was used. A 2-in. silicon wafer with a thickness of 260 μm was used as a substrate, Fig. 3(a). The substrate thickness was chosen so that together with the CNTs length, the device would fit into the measurement fixture, presented in [6]. First a layer of primer HMDS was spun and then AZ5214 negative photo resist was spun. After lithography, the catalyst consisting of 5 nm aluminum followed by 2 nm iron was evaporated in the same run using an electron beam evaporation machine, Evaporator Lesker, and the lift-off was carried out in 1165 remover, Fig. 3(b). The bundles of vertically aligned CNTs were grown using thermal CVD in AIXTRON NanoInstruments Black Magic, Fig. 3(c). Two gases, hydrogen and acetylene with flow rate of 700 sccm and 200 sccm were used in the growth process where the acetylene was a source gas and hydrogen was a carrier gas. The hydrogen gas keeps the active sites of catalyst clean from carbon deposition during growth and stops the deposition of amorphous carbon on the surface of catalyst. First, the catalyst was pre-treated at 500 °C for 3 min in the environment of continuous flow of hydrogen gas at around 8 mbar pressure which reduces the iron oxide catalyst particles into iron particles and activate them as well. Then the temperature was raised to 700 °C within a few seconds and acetylene gas was introduced in the chamber.

The schematic diagram of the thermal CVD growth system is shown in Fig. 4. The system is partially automatic and controlled by computer software. It is equipped with three high mass flow controllers, each has the ability of flowing two types of gases. One of the flow controllers is dedicated to the carbon source gases while the second one to carrier gases and the third one to inert gases. These can be calibrated for a specific gas within few seconds and these are calibrated for hydrogen, acetylene and nitrogen gases here. The hydrogen and acetylene are brought from the mass flow controller using individual lines into a single line where they mix together. This mixture of gases is introduced through the shower head on the sample heated at growth temperature and finally the rest of the gases are pumped out after use. The gases are flown in and out such that the pressure in mbar inside the chamber remains the same during the growth process. The heater is heated up to 700 °C in hydrogen environment and cooled down to room temperature within few minutes in nitrogen environment making the complete process very fast.

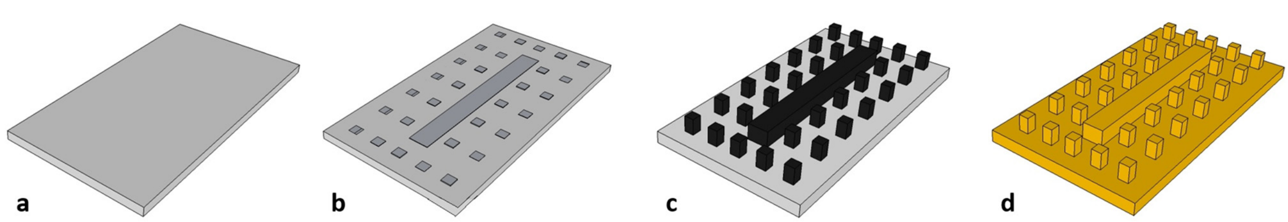

Fig. 3. Process plan of the resonator. (a) 2 in. silicon wafer of thickness around 260 μm. (b) Definition of catalyst using lithography. (c) Growth of CNTs using thermal CVD. (d) Deposition of aluminum/titanium/gold conductive seed layer.