UNIVERSITI TEKNOLOGI MARA

CO-PLANAR MICROWAVE INTEGRATED CIRCUIT TRANSMISSION LINES BASED ON CARBON NANOTUBE AND GRAPHENE

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PhD

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CONFIRMATION BY PANEL OF EXAMINARS

I certify that a panel of examiners has met on 6th November 2015 to conduct the finalexamination of Mohsen H. S. Ben Kara on his Doctor of Philosophy thesis entitled "Co-planar Microwave Integrated Ciruit Transmission Lines Based on Carbon Nanotube and Graphene" in accordancewith Universiti Teknologi MARA Act 1976 (Akta 173). The Panel of Examiners recommends that the student be awarded the relevant degree. The panel of Examiners was as follows:

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I declare that the work in this thesis was carried out in accordance with the regulation of Universiti Teknologi MARA. It is original and is the results of my own work, unless otherwise indicated or acknowledgment as referenced work. This thesis has not been submitted to any other academic institution or non-academic institution for any degree or qualification.

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ABSTRACT

The aim of this work is to study the feasibility of using carbon nanotube and graphene as new conductor materials for microwave integrated circuits (MMIC). As the dimensions of integrated circuits scale down to nanometers, the conductor resistance at high frequencies increase due to skin effect, and consequently the performance of MMICs degrade. Nanomaterials based on carbon are therefore proposed in this study as new material for MMIC due to their promising electrical properties including high mobility, high current densities, and negligible skin effect. Co-planar transmission lines were built from carbon nano-tube (CNT) and graphene using techniques compatible with semiconductor processing. In this work CNT was grown on Ni-coated Si wafers using a modified thermal CVD method, the Ni acting as growth catalyst. The optimal conditions were 900 °C reaction temperature, 4 nm catalyst thickness and 100 bubbles/min. gas flow rate. In addition, graphene was etched using a modified process which offer layer-by-layer etch, thus offering easy process control. The physical properties of both CNT and graphene films were analyzed using optical, SEM, FESEM and EDS for microstructure analysis, and Raman spectroscopy for crystalline analysis. The Raman results show both samples had well-graphitized carbon structures. A two-point probe station used to measure dc resistivity revealed the resistivity value of CNT of 6.3×10^{-5} Ω-m, whereas the graphene resistivity was 1.5×10^{-6} Ω-m. This indicated graphene to have better conductivity than CNT. Test structures in the form of co-planar transmission lines made of CNT and graphene were formed on Si wafers and characterized from 2 to 20 GHz. These structures were first analyzed using *CST* electromagnetic simulator to predict the RF performance. The structures were then fabricated using standard semiconductor processing steps, and their characteristics later measured using *Cascade Microtech* probe station connected to a vector network analyzer. Improved accuracy was obtained using Thru-Reflect-Line (TRL) calibration technique, as opposed to the more common SOLT method. The microwave properties of these nanomaterials were then extracted through two methods, namely curve-fitting of measured data with simulation, and RLC lumped-element circuit modeling in *Genesys*, from which the material parameters were extracted. From the modeling it was found that graphene had RF conductivity of 3.2×10^4S/m,better than those reported by other workers. Comparing with CNT, the results indicated graphene offered better transmission capability. The impedance of graphene lines were more easily controlled than those of CNT, and this allowed better impedance matching, resulting in reduced signal reflection at the line inputs. Comparison with Au and Cu showed graphene outperformed these traditional MMIC materials by showing more consistent performance throughout the bandwidth, with almost zero skin effect. This is a significant result since with micro-scale circuits skin effect will become dominant at high frequencies. Although very thin layers of graphene were used here, the skin effect was found to be negligible compared to Au or Cu. The use of graphene as new interconnect materials thus could help improve MMIC performance by offering monolithic inter-connect ability between various active and passive devices with little loss, and with improved higher frequency performance owing to the negligible skin effect.

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