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Effect of Electrical Contact Resistance in a Silicon Nanowire Thermoelectric Cooler and a Design Guideline for On-Chip Cooling Applications

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Contact resistance gains prominence as feature size reduces to the nanometer length scale. This work studies the effects of electrical contact resistance on the performance of silicon nanowire-based thermoelectric coolers using COMSOL Multiphysics. The values of the contact resistance used to simulate the impact are experimentally extracted from a pair of thermoelectric legs with each leg made of top-down-fabricated 100 silicon nanowires having diameter of 100 nm. Analytical models agreeing well with the simulation results are provided. Lastly, a design methodology is proposed for optimum performance in on-chip cooling applications.

Key words: Silicon nanowires, thermoelectric, on-chip cooling, design

INTRODUCTION

Transistor scaling has brought about uneven heat fluxes and thermal maps along with the technical advances. In today's 32-nm technology node localized heat fluxes can surpass 300 W cm^{-2}, while for optoelectronics devices the intensity can even exceed 1000 W cm^{-2}.[1–3] High heat flux, if not removed quickly, degrades circuit performance and reliability. Thus, there is an increasing need for better, localized cooling solutions such as embedded thermoelectric coolers (eTEC). Silicon nanowire (SiNW), with its material merits and improved thermoelectric properties over bulk silicon, is a potential candidate for use in active cooling solutions.[4–6]

Recently, Zhang et al.[7,8] investigated the thermoelectric performance of SiNW using numerical simulation. However, the reported results were based on zero contact resistance (ideal case) and do not fully the scenario in the real world. While contact resistance is less of a concern for bulk material TEC (mm^2-sized contact per thermoelectric leg[9]), its impact in nanostructures cannot be underestimated.[10] Furthermore, current studies of SiNW as a good thermoelectric material are limited to the fundamental level of individual SiNW.[4–6,11] More work on SiNW-based thermoelectric devices needs to be done for the benefit of further development.

In this work, we address the effect of contact resistance in a SiNW TEC system simulated using numerical simulation software (COMSOL Multiphysics) and propose a methodology to design a SiNW eTEC. We provide analytical models incorporating the effect of contact resistance that match well with the maximum cooling and maximum heat removed characteristics. Considering its good accuracy at the micrometer length scale,[12] which is the typical SiNW length required for effective cooling, the macroscale classical heat transfer model is utilized for simulating the thermoelectric performance of SiNW. Prior to the simulation process, the electrical resistivity values of the SiNW are experimentally extracted from a SiNW-TaN/Al system fabricated using the complementary metal–oxide–semiconductor (CMOS) process, while the thermal conductivity and Seebeck coefficients are taken from acknowledged literature reported values.[5]

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