Implementation of Full Carbon-Based Three-Dimensional Interconnects

Abstract

As the scaling of device size is reaching to the fundamental physical limitations, the escalating cost of following Moore's Law has pivoted the semiconductor industry's focus to More-than-Moore (MtM) technologies. Supported by advanced packaging solutions, high-density heterogeneous integration of analog/mixed-signal, RF, MEMS and image sensing with CMOS in a variety of 2.5D and 3D architectures at system level is expected to be one of the main driving forces for the future growth of electronic products.

Carbon nanomaterials, graphene and carbon nanotubes (CNTs) emerge as promising materials for the integration in the next-generation advanced packaging technologies in recent years. The main benefits of carbon nanomaterials lie in their excellent electrical, mechanical and thermal properties: i.e. their low resistivity, high current density, low coefficient of thermal expansion (CTE) and high thermal conductivity. These advantages enable carbon nanomaterials to be a highly attractive candidate as both on-chip and off-chip interconnects in 3D integrations.

Most recently, full carbon-based three-dimensional (3D) interconnects through an integration of one-dimensional (1D) carbon nanotubes and two-dimensional (2D) graphene were proposed, expected to have better out-of-plane and in-plane properties than their metal counterparts. In this thesis, we designed and developed the fabrication process flow to implement CNT-graphene heterostructure as filler of through silicon vias (TSVs) for novel 3D interconnects. In this approach, vertical-aligned CNTs replaced the conventional metals in TSVs, while the traditional horizontal metal lines were replaced by graphene. The key challenges include, but are not limited to (1) process development of high density CNT bundles growth within TSVs on the bottom graphene electrodes, (2) transfer process of a top graphene layer onto the as-grown CNT bundles and (3) electrical studies of the contact formed between CNTs and top graphene layer after the assembly process.

One of the significant outcomes of this thesis is to successfully demonstrate the growth of CNTs within TSVs on the bottom graphene electrodes. Firstly, the fabrication processes of top wafer with TSVs of various diameters (5-50μm) and bottom wafer with patterned graphene electrodes and catalyst deposition were successfully developed. Next, top TSV wafer and bottom graphene

wafer were bonded and manually ground, followed by wet and dry etching to completely remove the handling wafer and buried oxide to expose the underlying TSVs. CNT growth was conducted successfully both within TSVs and free-standing on the graphene layer. However, compared to the free-standing growth with sufficient length (~334μm) and high density estimated as $\sim 10^{11}$ cm^{-2}, there were few CNTs grown within the via holes. The inhibited growth of CNTs within the unfilled-TSV can possibly be attributed to several process-engineering steps involved e.g. wafer-bonding, grinding and wet/dry etching.

On the other hand, transfer process of a top graphene layer onto the as-grown CNT bundles was successfully performed with direct graphene-to-CNT contact at the interface. Four-point-probe (4PP) I-V characterization suggests that an ohmic contact was achieved between the graphene and CNTs. Low CNT bump resistance of 2.1Ω for 90,000 μm^2 CNT area including the CNT/graphene contact resistance was obtained, demonstrating reduction of contact resistance between CNT and Au under the same fabrication and measurement conditions. This part of the thesis presents the preliminary results for the assembly process of top-transferred graphene on CNTs and the electrical property of direct CNT/graphene contact, paving the way for the implementation of full carbon-based 3D interconnects.

For the future work, further modification and optimization of the process steps need to be done in order to attain higher CNT fillings within the TSVs on the bottom graphene electrodes. Moreover, fusion of the graphene and CNTs with carbon covalent bonds needs to be explored in order to further decrease the contact resistance and enhance the reliability of the carbon-based 3D interconnects.