Low-Resistivity Long-Length Horizontal Carbon Nanotube Bundles for Interconnect Applications—Part I: Process Development

Hong Li, Member, IEEE, Wei Liu, Member, IEEE, Alan M. Cassell, Franz Kreupl, Member, IEEE, and Kaustav Banerjee, Fellow, IEEE

Abstract—Although horizontally-aligned carbon nanotube (HACNT) interconnects are the most common scenarios that have been modeled and analyzed in theoretical research, fabrication of HACNT test structures has remained an enigma until now. Through addressing several fabrication challenges, this paper reports a novel process that enables fabrication of high-density, long (over hundred microns), and thick (up to micrometer) HACNT interconnects. Furthermore, horizontal CNT-based 2-D Manhattan structure is demonstrated by properly designing the catalyst and flattening process. These structures are crucial for building angled interconnects and on-chip passive devices. In addition, to address the contact issue between metal and thick HACNT bundles, a multistep lithography combined with specifically designed metal deposition technique is performed to ensure full contact configuration. Using such a process, test structures with arrays of various sizes of HACNT bundle interconnects are fabricated. The process developed in this paper provides an important platform for future research and technology development of CNT-based interconnects and passive elements.

Index Terms—Carbon nanotubes (CNTs), chemical vapor deposition, contact, horizontally aligned, interconnects, Manhattan structure, resistivity.

I. INTRODUCTION

INTERCONNECTS in advanced very large scale integrated circuits, based on Cu are confronting an acute problem in terms of performance and reliability because of significant size effects resulting in a sharp rise in resistivity and degradation in current carrying capacity [1], [2]. Carbon nanotubes (CNTs) have shown promise in many ways, because of their excellent electrical, thermal, and mechanical properties [3]–[5], to potentially solve the performance and reliability requirements of both horizontal and vertical interconnects for next-generation electronics [6]–[8]. Since the first demonstration of CNT-based vertical interconnects (vias) [9]–[11], research in both theoretical and experimental aspects of CNT interconnects has progressed significantly [6], [12]–[19].

It should be noted that while most CNT interconnect modeling works have focused on the applicability of CNTs as horizontal interconnects, the fabrication of horizontally aligned carbon nanotube (HACNT) bundles with long length (>100 μm) has remained challenging. Such long length HACNT fabrication is important because the resistivity of CNT reduces as length increases due to the existence of quantum contact resistance \( R_Q \) [6]. This can be observed from the CNT resistivity \( \rho_{CNT} \) calculation: \( \rho_{CNT} = A(R_Q/L + R_S/\lambda) \), where \( A \) is the area, \( L \) is the length, \( R_S \) is the per unit length scattering resistance, \( \lambda \) is the mean free path [16, Fig. 3]. Particularly, as shown in [14], multiwalled carbon nanotubes (MWCNTs) have large mean free path, and their resistivity saturates after ~100-μm length. In addition, for practical interconnect schemes in current IC designs, repeaters are inserted along long interconnects to reduce delay [20]. In advanced IC technologies, the optimal length of interconnect segment between two repeaters is on the order of 100 μm [20].

In addition to the length requirement, there is also a requirement for the thickness of CNT bundles. Monolayer CNT arrays have been fabricated, but they are not suitable for general interconnect applications because of their large resistance (they might have some benefits for very short local interconnects with minimum driver size [6]). Large thickness is a straightforward way to reduce the resistance as the resistance is inversely proportional to the thickness. From practical design aspects, the latest International Technology Roadmap for Semiconductors [21] predicts the global interconnects to have thickness in the range of 136–2340 nm for the 22-nm technology node. Furthermore, micrometer thick interconnects are also important for many high-frequency applications, where the resistance of wires needs to be small to minimize high-frequency losses. More specifically, the large thickness of CNT bundles is of particular interest and vital for demonstrating the unique high-frequency properties (reduced skin effect) of CNT bundle interconnects as predicted in [16], where the thickness of CNT bundles must be large enough.
to allow skin effect to take place. In addition, long and thick CNT interconnects are necessary for off-chip applications to maximize both thermal and electrical advantages of CNTs [7], [12].

In this paper, we report a novel process that allows fabrication of long (over 100 μm) and thick (up to micrometer) HACNT bundle interconnects using a liquid-assisted flattening technique. This paper is organized as follows. Section II begins with a review of the current status and challenges of HACNT bundle fabrication and then highlights the novelty of this research. Section III provides the details about the proposed process. Section IV addresses the critical issue of contact that is associated with all HACNT bundles and illustrates the techniques employed to lower the metal-CNT bundle contact resistance. Section V demonstrates the fabrication of test structures and their electrical characterization. Conclusions are drawn in Section VI.

II. STATUS AND CHALLENGES OF FABRICATING HACNTS

Although the importance of long-length and thick HACNT bundles is unquestionable, to develop such a fabrication process has always been a challenging task. Many efforts have been pursued in this direction, but not many have succeeded in demonstrating long HACNT bundles over the last decade [11], [22]–[35], [37]. In fact, nearly all results from rather limited existing reports are yet to be satisfactory as the fabricated CNT bundles were either too short in length or too small in thickness (or monolayer arrays in some cases).

The most common approach to grow horizontal CNT bundles used the fact that CNTs always tend to grow perpendicular to the catalyst surface [11], [22]–[24]. It, however, requires challenging catalyst deposition techniques and the growth tends to stop after several micrometers. Recently, Lu et al. [25], deposited catalyst on the trench sidewalls and had CNT bundle grown inside the trench without interacting with the substrate to reach several tens of micrometers [25]. The sidewall, however, could not be fully covered by the catalyst, resulting in poor CNT coverage, which not only causes controllability issue, but also limits the thickness of the CNT bundles. In addition, practical integration with CMOS process using this technique to make test structures remains unclear. Another often used approach is to direct the growth by electric field, either from an external bias [26] or from a self-generated one in the plasma environment [27], [28]. These growth techniques, however, mostly yield short length (~10 μm) and small thickness (with few CNT layers) as well as low density. Other approaches have also been pursued such as gas-flow guiding [29], [30], ac dielectrophoresis [31], [32], and crystallographic interactions with the substrate [33], [34]. All of these techniques mostly yielded small thickness or monolayers. Even though a CNT interconnect was demonstrated to operate at 1 GHz with silicon transistors [31], the CNT length was very small (~5 μm) and not in the bundle form because of its process limitations.

A completely different approach has also been pursued to obtain HACNTs in two steps. At first, CNTs are grown vertically and then flattened into horizontal orientation, either using mechanical rolling [35] or by liquid-assisted techniques [36], [37]. Since growth of long vertically aligned carbon nanotube (VACNT) bundles has been demonstrated in the literature, long HACNT bundles can be achieved, in principle, following such an approach, provided that the flattening process is successful. For such a scenario [shown in Fig. 1(a)], the thickness of HACNT (t) after flattening is determined by the initial thickness (T) of as-grown VACNT (identical to the catalyst dimension) and the degree of shrinking during the flattening process (densification ratio \( D_R = T/t \)). The width of CNTs (W) during flattening remains almost the same. While these methods can potentially solve the short length problem, the approaches demonstrated in [35]–[37] have difficulties in achieving micrometer thick HACNTs with reasonably small widths and low contact resistance.

One must note that the flattening process requires VACNT bundles (or catalyst patterns) to have rectangular shape with aspect ratio larger than one to obtain good control of the flattening orientation and the width of HACNTs. Fig. 1(b) and (c) show that CNT bundles with \( W/T \) close to 1 yield poor flattening and width control using liquid-assisted technique. For large \( W/T \) as shown in Fig. 1(b), the CNT bundle was not flattened but rather arched because of large self-supporting force of VACNT. For small \( W/T \), as shown in Fig. 1(c), the CNT bundle was flattened but in a random orientation. Generally, \( W/T \) should be >3 to have a good control of the flattening orientation. Such high aspect ratios provide imbalanced surface tension and effective capillary force along different directions [inset of Fig. 1(a)], thus providing anisotropic shrinkage and controllable flattening. Therefore, fabrication of micrometer thick HACNT bundles using this flattening process requires much larger width (W) of patterned catalyst. This high aspect ratio requirement limits the applicability of this technique. For instance, to obtain \( t = 1-\mu \text{m-thick HACNT} \), T needs to be 30–50 μm (densification ratio \( D_R = 30–50 \)), so W needs to be >90–150 μm, which is very large for interconnect applications, especially on-chip wires. A novel technique needs to be developed to
solve this high aspect ratio issue to make this flattening process versatile. In addition, making contacts with CNT bundles has always been an important issue. There will be additional challenges for contacting thick horizontal CNT bundles, as will be shown in this paper. This problem could not be investigated before because of lack of thick CNT bundle fabrication process.

In addition, 2-D Manhattan interconnect structures, which are widely employed in ICs, have not yet been demonstrated with CNTs. Currently, both mechanical rolling [35] and liquid-assisted flattening [37] can only obtain HACNTs along a single orientation. The ability to construct 2-D Manhattan structure would be useful to build test structures for many applications (for example, on-chip inductors) and greatly enhance the applicability of this process.

In this paper, we report a novel and scalable process that not only allows fabrication of long (>100 μm) and thick (up to micrometer) HACNT bundle interconnects, but also enables the construction of 2-D Manhattan structures. Flattening of multiple VACNTs in a single step is developed to address the high aspect ratio requirement. The 2-D Manhattan structure made of horizontal CNT bundles are constructed by designing the catalyst structure and engineering the flattening process. Using the developed process, arrays of HACNT bundle interconnect structures are fabricated with uniquely engineered metal-CNT contacts. The process developed in this paper provides an attractive platform for research and technology development of CNT-based interconnects and passive elements. The comprehensive electrical and self-heating characterization of the HACNT interconnects are discussed in the companion paper [38].

III. FABRICATION OF HORIZONTAL CNT BUNDLES
A. Overall Process Flow

To comply with microelectronics for interconnect applications, high-resistivity silicon wafer was chosen to be the starting substrate. Silicon dioxide (SiO$_2$) and aluminum oxide (Al$_2$O$_3$) serve as insulating layer as well as buffer layer for Fe catalyst. The fabrication process flow for VACNT bundles is shown in Fig. 2 and is briefly described as follows. The Fe catalyst is 1.5-nm thick and patterned into strips (dimensions depend on desired VACNT) before thermal CVD to grow the CNTs. C$_2$H$_2$/H$_2$ gas rates are 20/700 sccm at 8-mbar pressure and the growth temperature is 750 °C. The growth chamber employs a bottom and top heated reactor [39] to provide relatively uniform growth. The as-grown CNTs are vertically aligned MWCNTs as shown in Fig. 3(a). The length of VACNTs in this paper is 150–200 μm and can be controlled by the growth time. The grown CNTs have good quality as confirmed by the Raman spectra in Fig. 4(a) and are characterized as MWCNTs with an average diameter of 7 nm with three shells [Fig. 4(b)].

The samples are subsequently treated with isopropyl alcohol (IPA) solvent to concurrently densify and flatten the VACNT bundles to horizontal orientation [Fig. 2(d)]. Once the CNT bundles are flattened on the substrate as HACNTs, standard microelectronics processing (such as photolithography and etching) can be used to pattern the HACNTs and to make contacts. Finally, contacts are patterned and metals (Ti/Au) are deposited to build the interconnect structures. More details about certain critical steps are discussed later.

B. Control of Flattening

Fig. 3(a) shows one CVD grown VACNT bundle from one of the catalyst strips with $W = 30$ μm and $T = 7$ μm. The sample then goes through a liquid-assisted flattening process. This flattening process has been demonstrated in [36] to form CNT wafer and can be explained by capillary effect: IPA has good wettability to both CNT and substrate, and acts as adhesive between solid surfaces of CNTs/substrates to pull down vertical CNTs to form horizontal CNTs. In this paper, we chose IPA as the liquid because not only it can wet both CNT and substrate well, but also it can be easily evaporated at room temperature. One critical issue for this liquid-assisted flattening process is to control the orientation in which the VACNTs fall. To achieve better control of the flattening orientation, some external forces are needed to facilitate the flattening process to desired orientation. Here, we use the combination of gravitational force and force generated by the liquid flow. Two techniques are simultaneously employed to generate external force, as shown in Fig. 2(d): 1) sample tilted to 30°, facing the desired HACNT orientation downward and 2) a small amount of IPA is flowed through the sample surface, rather than immersing sample into IPA solvent. It is important to let the IPA flow out of the sample and only a small amount of IPA may remain on the sample to be evaporated.
Fig. 3. (a) As-grown VACNT bundle from catalyst dimension $W = 30 \mu m$ and $T = 7 \mu m$. (b) HACNT bundle obtained after flattening process. (c) HACNT bundle array showing good control of flattening orientation. (d) Zoom-in image of one of the HACNT bundles in (c).

Fig. 4. (a) Raman spectra of as-grown CNTs, indicating MWCNT (no radial breathing mode observed) and good quality (high $G/D$ ratio). (b) TEM image of an as-grown CNT, showing 6–8-nm diameter and three shells.

out. Both tilted sample and the IPA surface flow help to direct the orientation of the flattening process by contributing additional forces to the desired orientation. After flattening process, HACNT bundle arrays are formed on the substrate with good alignment as shown in Fig. 3(c). Note that this liquid-assisted process also densifies the CNT bundle, as has been reported in [40]. In this paper, the density of CNTs after IPA treatment was enhanced by $\sim 45$ times (densification ratio $D_R = 45$) as evidenced from atomic force microscope (AFM) measurement shown in Fig. 5. The width of HACNTs after flattening almost remained the same as the $W$ of the VACNTs.

It should be noted that to make sure that CNT bundles are flattened in a particular orientation, it is also important to have catalyst strip with high aspect ratio ($W/T$), as described in Section II. Larger $W$ implies larger surface, which introduces larger surface tension on $W$ side than that on $T$ side, so VACNT is more likely to flatten perpendicular to the $W$ side. If $W$ and $T$ are similar, then surface tensions on both sides are similar, and there is no preference on the flattening orientation. From our experiments, with reasonable $W/T$ ratio ($>3$), vertical CNT bundles were found to be flattened in the orientation perpendicular to $W$, which is desired.

C. Obtaining Thick HACNTs

Because of the requirement of relatively large $W/T$ ratio and shrinking in thickness after flattening, it is difficult to obtain CNT bundles with large thickness (of the order of micrometer). To overcome this limitation, we introduce multiple VACNT flattening in a single step to obtain large thickness HACNTs. Instead of using one VACNT to form one HACNT, multiple VACNTs are designed to be flattened on top of each other to form one thick HACNT as shown in Fig. 6. Each as-grown VACNT still has large $W/T$ ratio to ensure the flattening orientation. The overlapping regions of the HACNTs have greater thickness depending on the number of VACNTs. The root and tip of CNT bundles are clearly observable and the number of VACNTs can be identified in the figure. Using this multiple VACNT flattening process, the total $W/T$ ratio is no longer needed to be large. We successfully fabricated $W = 30 \mu m$ with total $T = 40 \mu m$ ($4 \times 10 \mu m$ in parallel), which yielded a thickness of $\sim 1 \mu m$ after flattening and densification. Note that the concept of using multiple VACNTs in parallel should also work for the mechanical rolling-based flattening approach.

Although we are able to fabricate thick HACNTs by catalyst patterning and process engineering, our current process may encounter scalability issue as it would be quite challenging to flatten lines with small widths ($<1 \mu m$) while maintaining reasonable thickness. With some postprocessing, there are pathways to address this issue. For instance, one can first
fabricate large width HACNTs with desired thickness and then pattern them to achieve the desired smaller widths. Many future engineering and development research can be carried out along this direction.

D. Constructing 2-D Manhattan Structures

The 2-D Manhattan structures involve perpendicularly aligned interconnect structures and are commonly used in current back-end layout designs to achieve the shortest-path communication between logic gates [41]. The most common way to achieve this is to orient adjacent interconnect layers in perpendicular directions by connecting through vertical vias.

For CNT interconnects, fabricating single orientation interconnect is challenging enough, let alone making 2-D Manhattan structures. In this paper, we demonstrate how to overcome this challenge and build Manhattan structures for the first time. Based on the understanding of the liquid-assisted flattening process, we further develop a process that could successfully construct 2-D Manhattan structures in a single step by suitably engineering the catalyst design and flattening process. Fig. 7(a) shows the placement of as-grown VACNTs, and Fig. 7(b) shows the obtained Manhattan structure. The liquid flows from the top as shown in Fig. 7(a), which provides forces to flatten two VACNTs in perpendicular directions. Once the Manhattan structure is obtained, standard lithography can be used to pattern and build useful structures. Fig. 7(c) shows an example of using a Manhattan structure to build a planar spiral inductor that can be useful for designing various on-chip CNT-bundle-based inductors.

IV. OBTAINING GOOD CONTACTS TO THICK CNT BUNDLES

Making good contact to CNTs is always a challenging issue for both CNT-based transistors and interconnects. From process point of view, making good contacts to large-thickness horizontal CNT bundles has some additional issues that may not be encountered in the case of transistors or vertical vias. As shown in Fig. 8(a), an ideal contact should have metal physically contacting both sides as well as the ends of each CNT within the HACNT bundle. (b) Partial metal-HACNT contact with voids between metal and CNTs. (c) Thick HACNT would likely have PR residue at the bottom of CNT bundle as CNTs are good light absorbers. (d) Nonideal vertical HACNT edge profile after etching could introduce voids between metal and HACNTs.

1This is also the first demonstration of a Kanji character (meaning “father”) using any form of carbon nanostructures.
Therefore, any undercut or imperfect edge will induce void between metal and CNTs, leading to partial contacts [Fig. 8(b)]. This issue does not exist for either CNT array transistors (thin CNTs) or vertical CNT vias, where chemical mechanical polishing process is used to open up all the shells in each CNT to form good metal contacts.

To make good full contact between CNT bundle and metal, we first employed a two layer PR process to overcome the PR residue issue [Fig. 9(a)]. The bottom (first) PR layer in contact with the CNTs is polymethylglutarimide (PMGI), which can only be exposed by deep ultraviolet (DUV) and the top (second) PR layer can be any standard PR (AZ4110 in this work). After first exposure and develop of AZ4110, the unexposed top PR layer serves as a mask for subsequent exposure of bottom PMGI layer under DUV. Because the contact region is defined by first layer, we can expose and develop PMGI multiple times until there is no notable PR residue at the bottom of HACNT bundles. Note that increasing exposure and develop time for PMGI layer only increases the residue at the bottom of HACNT bundles. Increasing develop PMGI multiple times until there is no notable PR residue issue [Fig. 9(a)]. The bottom (first) PR layer is used to define the electrode pads and also serves as a mask for exposing PMGI under DUV. PMGI can be exposed and developed for multiple times until no PR residue is left. After multiple exposures, a PR undercut profile is also formed, which facilitates the lift-off process in the next step. (b) Sample is tilted and rotated simultaneously during metal deposition to make good full metal-CNT contact at both ends of the HACNT bundle.

![Fig. 9](image9.png) **Fig. 9.** (a) Using a two-layer PR process with standard PR (second PR) on top of PMGI, which can only be exposed under DUV. The top layer is used to define the electrode pads and also serves as a mask for exposing PMGI under DUV. PMGI can be exposed and developed for multiple times until no PR residue is left. After multiple exposures, a PR undercut profile is also formed, which facilitates the lift-off process in the next step. (b) Sample is tilted and rotated simultaneously during metal deposition to make good full metal-CNT contact at both ends of the HACNT bundle.

![Fig. 10](image10.png) **Fig. 10.** Test structure array with total of 54 devices with different widths, lengths, and thickness of CNT bundle interconnects. All of the HACNT interconnects in the test structure array show good horizontal alignment.

This tilted configuration exposes the lower most part of the HACNT bundle to metal beams during metal deposition, even if the HACNT edge is not perfectly vertical, thereby preventing possible voids between CNT and metal. In addition, the sample stage is rotated during metal deposition so that both ends of HACNT are exposed to the metal beam. Through combining two layer PR process as well as tilting and rotating the stage during metal deposition, all CNTs in the thick HACNT bundle get in full contact with metal thereby forming good contact configuration. In this paper, 500/1000-nm thick Ti/Au stack is deposited as contact electrode without any lift-off problem.

### V. Fabrication of HACNT Interconnect Array

Using this process, test structures were fabricated with various CNT interconnect length, width, and thickness. Fig. 10 shows an array of 54 devices (six rows and nine columns), where all HACNT bundles are flattened in the same orientation. It should be noted that this process also allows cofabrication of CNT bundle with different thickness, which can be beneficial for designing both interconnects and passives on the same layer. For the same width and thickness, the length of CNT interconnects were varied from 10 to 130 μm. Using TLM-like technique [42], the resistance of CNT interconnects with different lengths was measured, and the resistance per unit length \( R_{p.u.l} \) and contact resistance \( R_{cont} \) of CNT interconnect for a given width and thickness were extracted using the equation as follows:

\[
R_{\text{meas}} = R_{\text{p.u.l}} \times L + 2R_{\text{cont}}
\]

where \( R_{\text{meas}} \) is the measured resistance for a given length \( L \) of CNT interconnect. Fig. 11 shows an example of the measurement data for four different CNT interconnect thickness with fixed line width \( W = 30 \ \mu m \). Similar to the CNT bundles shown in Fig. 6, the CNT interconnects measured in Fig. 11 were flattened from one to four VACNT bundles (each VACNT bundle has \( W = 30 \ \mu m , T = 7 \ \mu m \)). Each data point in Fig. 11 is the average measured value from three to six devices (deviations of data points are mostly <10%). Even though all the CNT interconnects are individual devices, the data points display clear linear relationship, which indicates that the HACNTs have reasonably uniform spatial density, which in turn implies success of our TLM-like test structure fabrication and measurements.
The extracted resistance per unit length and contact resistance are shown in Table I. It can be observed from the extracted resistances that the overall resistance per unit length and the contact resistance, in general, scale with the cross section of the HACNTs. The resistance per unit length is more or less inversely proportional to the thickness as expected, indicating the feasibility and success of the process of making full metal-CNT-bundle contact discussed in Section IV. The unit area contact resistance is calculated to be on the order of 1 E–10 Ω-m². Table I also shows the results for catalyst strip with W = 40 μm and T = 10 μm. For this configuration, the thickness of CNT bundle can reach up to micrometer thickness when there are three or four catalyst strips. Because of larger thickness and width, both per unit length and contact resistances are generally smaller than those HACNTs with W = 30 μm and T = 7 μm. In part II, we provide more discussions on the electrical data and show that the resistivity of our CNTs is between 1.7 and 4.1 mΩ-cm [38].

VI. CONCLUSION

To summarize, in this paper, thick (~1 μm) HACNT interconnects with lengths (>100 μm) have been demonstrated by designing novel catalyst structures and using a liquid-assisted flattening process. The developed process also enables construction of 2-D Manhattan structures in a single step, thereby opening up endless possibilities of realizing CNT-based on-chip passive elements such as angled interconnects, inductors, and antennas in next-generation integrated circuits and systems. Special process has also been developed to make full metal contact with thick horizontal CNT bundles. Through fabricated test structures, the per unit length resistance and contact resistance of CNT interconnects were extracted using TLM-like measurements, indicating the success of the process. The ability to fabricate long and thick horizontal CNT interconnects not only fills the gap between CNT interconnect modeling and experimental efforts, but also provides an important vehicle to study certain fundamental properties of CNT bundles, such as their unique high-frequency properties (i.e., reduced skin effect), as well as extraction of relevant parameters. This experimental demonstration also opens up pathways for exploring many other process options (such as metal-filled CNT bundles) and applications (such as chip-to-chip interconnections, off-chip thermal bumps/links for efficient packaging, and heat sinking), as well as embedded energy-storage devices in emerging 3-D integrated circuits.

ACKNOWLEDGMENT

All process steps for device fabrication were carried out using the Nanostructure Cleanroom Facility at the California NanoSystems Institute and the Nanofabrication Facilities at UCSB - part of the National Nanotechnology Infrastructure Network. K.B. thanks the Alexander von Humboldt Foundation in Germany for the F.W. Bessel Research Award that greatly facilitated many stimulating discussions with F.K. in München.

Table I

<table>
<thead>
<tr>
<th>CNT Interconnects</th>
<th>W30-T7</th>
<th>W30-T7x2</th>
<th>W30-T7x3</th>
<th>W30-T7x4</th>
<th>W40-T10</th>
<th>W40-T10x2</th>
<th>W40-T10x3</th>
<th>W40-T10x4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance p.u.l. (Ω/μm)</td>
<td>8.036</td>
<td>3.555</td>
<td>2.488</td>
<td>1.957</td>
<td>2.616</td>
<td>1.306</td>
<td>0.871</td>
<td>0.681</td>
</tr>
<tr>
<td>Contact Resistance (Ω)</td>
<td>52.9785</td>
<td>16.05</td>
<td>13.9865</td>
<td>11.6485</td>
<td>38.0415</td>
<td>21.022</td>
<td>15.555</td>
<td>13.4895</td>
</tr>
<tr>
<td>Unit Area Contact Resistance (Ω-m²)</td>
<td>2.47E-10</td>
<td>1.5E-10</td>
<td>1.96E-10</td>
<td>2.17E-10</td>
<td>3.38E-10</td>
<td>3.74E-10</td>
<td>4.15E-10</td>
<td>4.8E-10</td>
</tr>
</tbody>
</table>

* Calculation is based on the assumption that the densification ratio is 45, as indicated in Fig. 5.

REFERENCES


Hong Li (S’07–M’12) received the Ph.D. degree in electrical and computer engineering from the University of California, Santa Barbara, CA, USA, in 2012. He is currently an Emerging Memory Engineer with Micron Technology, Inc., Boise, ID, USA.

Wei Liu (M’10) received the Ph.D. degree in chemistry from the Institute of Chemistry, Chinese Academy of Sciences, Beijing, China, in 2008. He is currently a Post-Doctoral Research Scholar with the University of California, Santa Barbara, CA, USA.

Alan M. Cassell received the Ph.D. degree in materials chemistry from the University of South Carolina, Columbia, SC, USA, in 1998. He is currently an Aerospace Engineer at Entry Systems and Vehicle Development Branch, NASA Ames Research Center, Mountain View, CA, USA.

Franz Kreupl (M’04) is a Professor of electrical engineering with Technische Universitat Muenchen, Muenchen, Germany.