Monolithic Integrated Antennas and Nanoantennas for Wireless Sensors and for Wireless Intrachip and Interchip Communication

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***Abstract*—Monolithic integrated antennas and nanoantennas based on silicon technology, carbon nanotubes, graphene, and nanostructure thin film technology are discussed. Monolithic integration of antennas and novel nanoelectronic devices yields interesting applications in wireless sensing and in wireless intrachip and interchip communication. In case of extreme miniaturization the electronic properties of the materials used in the antenna antenna structures yield interesting effects like slow-wave propagation.**

I. Introduction

As the structure size of circuit devices and components is continuously decreasing the same will hold for antennas and radiation elements used in integrated circuits for on-chip and chip-to-chip communication. Following the general scaling trend on-chip antennas will soon enter the μm- and even the nanometer regime.

The rate of signal transmission on or between monolithic integrated circuits is limited by the cross-talk and the dispersion due to the wired interconnects. An interesting option to overcome the bandwidth limitations is wireless chip-to-chip and on-chip interconnects via integrated antennas. The electromagnetic coupling of antennas may occur via waves radiated into space and scattered by objects or via surface waves.

In the frequency range above 60 GHz, **si**licon **m**illi**m**eterwave **i**ntegrated **c**ircuits (SIMMWICs) of only a few millimeters size may also include planar antenna structures. The integration of the antenna allows the direct coupling of SIMMWICs to the radiation field [1]–[3]. A 15 GHz on-chip wireless interconnect system integrating antennas in digital CMOS circuitry has been demonstrated in [4], [5]. A 15GHz intrachip wireless interconnect using integrated antennas consisting of a transmitter-receiver pair fabricated in 0.18 μm CMOS technology is described in [6]. Demonstration of intrachip wireless interconnects over 40 cm distance has been demonstrated in this work. Further work on wireless interchip communication has been presented in [7], [8]. Channel modeling of wireless interchip and intrachip communication has been performed in [9], [10]. An intrachip wireless interconnect system using meander monopole on-chip antennas and operating in a frequency band from 22 GHz - 29 GHz is described in [11].

In [12]–[15] the utilization of the electronic circuit ground planes as radiating elements for the integrated antennas has been proposed. This allows for optimal usage of chip area, as the antennas share the same metallization structure as the circuits. By exciting the interconnection structures in transmission line modes and the antennas in antenna modes the interference between circuit and antennas has been minimized.

A further considerable size reduction of integrated antenna structures my be achieved on the basis of carbon nanotubes (CNTs). CNTs exhibit exceptional electron transport properties, yielding ballistic carrier transport at room temperature with a mean free path of around 0.7 μm and a carrier mobility of 10 000 $\mathrm{cm}^2/\mathrm{Vs}$ [16], [17].

II. CMOS integrated antennas

Instead of dedicating chip area for the antenna the antenna can make use of the available on-chip metallization. This can be obtained by dividing the top-most metallization layer into patches and impressing an RF signal across the gap between the patches [14], [15]. A possible top view (a) and a cross-section view (b) of a CMOS IC with an integrated antenna is shown in Fig. 1. The circuit is manufactured on a high-impedance substrate in order to reduce the losses of the radiated field. The substrate is backed by a metallic layer. On the top of the substrate a low-impedance layer, required for the MOSFETs is manufactured. The active devices and the interconnects are arranged on top of the low-resistivity layer. The total thickness of the interconnects varies according to the number of layers required by the CMOS circuitry. The top-most metallization layer, depicted in black in Fig. 1 (b), contains the ground supply plane. The antenna patches are manufactured in this metallization layer.

The described antenna can produce no interference with the CMOS circuitry, because a transmission line of n conductors supports $n - 1$ transmission line modes and one antenna mode, for which the total current on the line is non-zero. The transmission line modes and the antenna mode are orthogonal. Additionally, the CMOS transmission line fields are confined only in a narrow region underneath the antenna, while the antenna field spreads all over the substrate thickness. The CMOS circuitry and the antenna can be further decoupled by using a carrier frequency for the wireless link much higher than the CMOS clocking frequency.

In the V-band, the guided wavelength is in the range of a millimeter. Therefore, an open-circuited slot with a length of about a millimeter will be a transmission line resonator with a resonance frequency in the V-band. Since the resonator is open, the standing wave pattern on it will excite radiation fields. An example of such an open-circuit slot antenna with its current distribution is presented in Fig. 2.

III. Nanoantennas with MOM tunnel diodes

An important element of a nanoantenna detector is the rectifying element which extracts a dc component from the rapidly-varying radiation-induced antenna currents. Semiconductor diodes are widely used, but they encounter frequency limitations for the mm-wave and long-wave infrared regime. It has been demonstrated that metal-oxide-metal (MOM) tunnel diodes can provide rectification for IR and even optical radiation [24]. Such MOM diodes are formed naturally at the overlap area between two antenna arms, e.g. for a dipole antenna [25]. The early work focused on symmetrical MOM diodes, i.e. diodes with the same metal for both electrodes (antenna arms). Such symmetrical MOM structures result in symmetrical current-voltage characteristics, and they need to be biased away from the origin of the I-V curve in order to yield a nonlinearity needed for rectification. This results in detector extra noise due to the bias, and added circuit complexity. Recent work has shown that asymmetrical MOM diodes can be formed by metal combinations with different work functions, such as Pt and Al, and the resulting asymmetrical I-V curves posses the required nonlinearity for zero bias [26]. In important issue for rectification at IR frequencies is the RC time constant of the rectifying element. For detection of 10 μm LW-IR radiation, the rectifying element has to be able to respond to 30 THz antenna currents. For a typical antenna resistance of 100 Ω, this limits the tunnel-diode capacitor area to less than 100 nm$\times$100 nm, which is challenging for fabrication. Recent work has demonstrated e-beam lithographically-

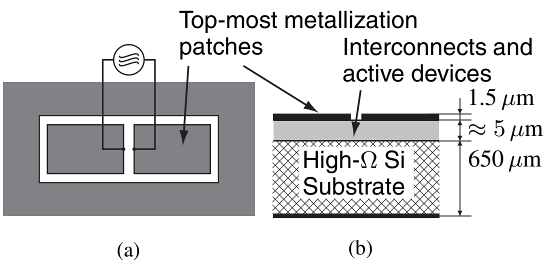

Fig. 1: A top view (a) and a cross-section view (b) of a chip with an integrated antenna.

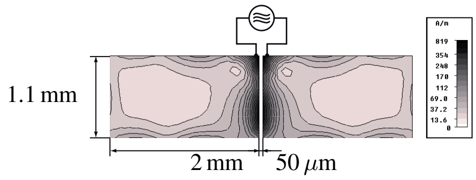

Fig. 2: Top view and current distribution of a two patch antenna, operating at 66 GHz.

defined dipole antenna structures with integrated MOM diodes that showed the expected polarization response and antenna-length dependence of dipole nanoantennas for 10 μm LW-IR radiation [27], [28]. In the future, we are planning to use nanoimprinting and nanotransfer techniques for the realization of the complete nanoantenna [29], [30].

IV. Nanoantennas based on carbon nanotubes (CNTs) and graphene

In 2004 Wang et.al. investigated random arrays of aligned CNTs and has shown show that the response to incident electromagnetic radiation is consistent with radio antenna theory [18]. The results of Wang stimulated the investigation of the fundamental properties of nanotube antennas and the question for wireless data transfer at the nanoscale [19].

From [20] an analytic expression for the surface conductance of a single-walled CNT was given that can be incorporated into the integral equations to account for the specific electron transport properties. In [21]–[23] copper and carbon nanoantennas are investigated using the modified integral equations which incorporate the CNT surface conductance. It was found that CNT dipoles start to go into resonance at much lower frequencies than assumed initially. This can be explained from the fact that electromagnetic waves are propagating along CNTs forming surface plasmons which have a reduced propagation velocity and thus shorter wavelengths. So CNT dipoles with several μm in length start to resonate in the low THz region where the wavelengths are 50 to 100 times longer compared to the length of the CNT dipole.

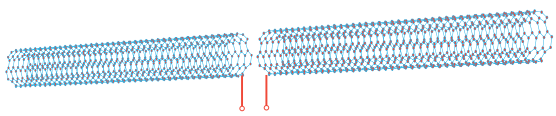

Fig. 3: CNT dipole antenna

Due to the slow-wave propagation of electromagnetic waves in CNT structures the wavelength of electromagnetic waves propagating in CNT structures is considerably smaller than the free-space wavelength. This effect occurs due to quantum transport effects in the CNT yielding a *quantum capacitance* and a *kinetic inductance* in addition to the geometric capacitance and inductance [31], [32]. In [31]–[33] a simplified equivalent circuit model of a CNT over ground according to Fig. 4 is presented with a kinetic inductance per unit of length L_K and a quantum capacitance per unit of length C_Q in addition to the geometry based inductance and capacitance per unit of length L_G and C_G, respectively. The phase velocity for the modified equivalent circuit is around $0.02 \cdot c_0$ which is in accordance with the reduced wavelength of the surface plasmons [34]. The appearance of slow-waves makes CNT antennas interesting for wireless communication between circuits at the micro- and nanoscale or between nanocircuits and the macroscopic environment [33], [35].

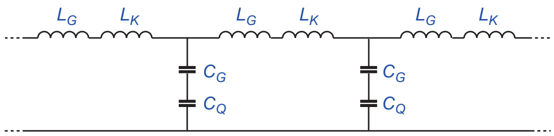

Fig. 4: Equivalent circuit model of a CNT over metallic ground plane.

Linear nanoscale dipole antennas, either made of metal such as gold or silver, or carbon nanotubes (CNTs) have been investigated [36], [37]. Fig. 3 shows a schematic drawing of a CNT dipole antenna. CNTs exhibit a very high inductance per unit length due to the high kinetic energy of the electrons [37]. The high inductance results in a slow-wave behavior where electromagnetic wave propagating along a CNT transmission line configuration have a phase velocity in the range of $c_0/100$ to $c_0/50$. This implies for a CNT dipole that the current wavelength on the dipole is much shorter in comparison to the wavelength of the source signal. In conclusion, CNT nanoantennas much shorter than the operating wavelength can be brought into resonance and potentially be used as radiation elements [33]. A similar effect can be observed in case of metal nanowires. Depending on the used material metals at optical frequencies exhibit a real part of the permittivity which is negative. Therefore surface plasmon polaritons can be excited along metal nanowires if irradiated by an optical signal [38]. The phase velocity of the surface plasmons is typically in the order of $c_0/10$. These effects suggest, that CNT dipoles or metallic nanoantennas can operate at wavelengths which are large compared to the length of the dipole. However, the slow-wave effect due to the kinetic inductance in CNTs gets lower for frequencies in the microwave region [39]. In case of metallic nanoantennas the permittivity is no longer negative at frequencies below optical frequencies and thus no surface plasmons can propagate along the metallic nanowire.

Due to the extremely high aspect ratio (length/cross sectional area), both, metal nanowires as well as CNTs have AC resistances per unit length in the order of several kΩ/μm [36]. This high resistance causes high conduction losses and thus seriously decreases the efficiency and the achievable gain of nanoantennas. In [37] the efficiency of a CNT dipole antenna is estimated to be in the range of -60 to -90 dB which results from the high conductance losses. The situation in case of metal nanoantennas will be similar. Although low power levels are sufficient in modern communication links the inherent loss introduced by metallic or CNT nanoantennas limits their applicability considerably. One approach to bypass the resistance problem could be the usage of arrays of nanoantennas or a bundle of parallel nanowires. In this case the resistance can be decreased to an acceptable value, but on the other side the slow-wave effect gets lost, as discussed in [39]. Thus, by an appropriate choice of geometry and the number of nanowires the properties of nanoantenna structures have to be optimized.

Novel antenna geometries without analog in conventional antenna technology have been suggested [36], [37]. In [36] metamaterial based CNT nanoantennas have been suggested.

Another promising alternative could be planar structures such as 2D graphene layers. Graphene is a two-dimensional material consisting of a monoatomic layer of carbon atoms ordered in a honeycomb structure as depicted in Fig. 5 [40]–[42]. It exhibits an excellent crystal quality and unique electronic properties [43]. Morozov et.al. have shown that electron-phonon scattering in graphene is so weak that room temperature electron mobilities as high as 200 000 cm^2/Vs can be expected if extrinsic disorder is eliminated [44].

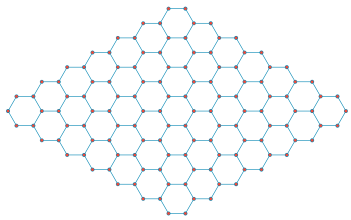

Fig. 5: Structure of a graphene layer.

Like CNTs graphene also exhibits excellent conductivity and slow wave properties [45], [46]. The achievable slow-wave effect in plasmon modes is in the order of $c_0/100$. At THz frequencies a population inversion in the graphene layer can be realized by optical pumping or forward bias which yields an amplification of the surface plasmon. Graphene allows the realization of planar structures and also the realization of active circuits [47].

V. Outlook

Intrachip and interchip wireless broadband communication at millimeterwave carrier frequencies can be realized in CMOS technology and will allow the transfer of Gbit/s data rates. Using segmented ground metallizations as antenna elements allows the integration of antenna structures without additional chip area consumption. A further size reduction of antenna structures will be possible by integration of CNT and graphene antenna structures. This will be interesting in connection with future RF CNT and graphene FETs and graphene based ICs. With the advancement of miniaturization MIMO systems using space multiplex may also be realized.

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References

[1] J. Büchler, E. Kasper, P. Russer, and K. M. Strohm, "Silicon high–resistivity–substrate millimeter–wave technology," *IEEE Trans. Microwave Theory Techn.*, vol. 34, pp. 1516–1521, Dec. 1986.

[2] P. Russer and E. Biebl, “Fundamentals,” in *Silicon-Based Millimeter-Wave Devices*, ser. Springer Series in Electronics and Photonics, J. F. Luy and P. Russer, Eds. Berlin Heidelberg New York: Springer, 1994, no. 32, pp. 149–192.

[3] P. Russer, “Si and SiGe millimeter-wave integrated circuits,” *IEEE Trans. Microwave Theory Techn.*, vol. 46, pp. 590–603, May 1998.

[4] B. Floyd, C. Hung, and K. Kenneth, “A 15-GHz wireless interconnect implemented in a 0.18-μm CMOS technology using integrated transmitters, receivers, and antennas,” in *VLSI Circuits, 2001. Digest of Technical Papers. 2001 Symposium on*, 2001, pp. 155–158.

[5] K. O, K. Kim, and B. Floyd et al, “The feasibility of on-chip interconnection using antennas,” in *Computer-Aided Design, 2005. ICCAD-2005. IEEE/ACM International Conference on*, 2005, pp. 979–984.

[6] J. Branch, X. Guo, L. Gao, A. Sugavanam, J. Lin, and K. O, “Wireless communication in a flip-chip package using integrated antennas on silicon substrates,” *Electron Device Letters, IEEE*, vol. 26, no. 2, pp. 115–117, 2005.

[7] K. O, K. Kim, and B. Floyd et al, “On-chip antennas in silicon ICs and their application,” *Electron Devices, IEEE Transactions on*, vol. 52, no. 7, pp. 1312–1323, 2005.

[8] ——, “Silicon integrated circuits incorporating antennas,” in *Custom Integrated Circuits Conference, 2006. CICC ’06. IEEE*, 2006, pp. 473–480.

[9] Y. P. Zhang, Z. M. Chen, and M. Sun, “Propagation mechanisms of radio waves over Intra-Chip channels with integrated antennas: Frequency-Domain measurements and Time-Domain analysis,” *Antennas and Propagation, IEEE Transactions on*, vol. 55, no. 10, pp. 2900–2906, 2007.

[10] Z. M. Chen and Y. Zhang, “Inter-Chip wireless communication channel: Measurement, characterization, and modeling,” *Antennas and Propagation, IEEE Transactions on*, vol. 55, no. 3, pp. 978–986, 2007.

[11] M. Sun, Y. P. Zhang, G. X. Zheng, and W. Yin, “Performance of Intra-Chip wireless interconnect using On-Chip antennas and UWB radios,” *Antennas and Propagation, IEEE Transactions on*, vol. 57, no. 9, pp. 2756–2762, 2009.

[12] H. H. Yordanov and P. Russer, “Integrated on-chip antennas for chip-to-chip communication,” in *Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE*, 2008, pp. 1–4.

[13] H. Yordanov and P. Russer, “Chip-to-chip interconnects using integrated antennas,” in *European Microwave Conference*, Amsterdam, The Netherlands, Oct 2008, pp. 777–780.

[14] ——, “Wireless inter-chip and intra-chip communication,” in *Proceedings of the 29$^{\rm th}$ European Microwave Conference 2009*, Rome, Italy, 2009.

[15] ——, “Integrated on-chip antennas using CMOS ground planes,” in *Proceedings of the 10$^{\rm th}$ Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems*, New Orleans, LA, 2010, pp. 53–56.

[16] C. Dekker, “Carbon Nanotubes as molecular quantum wires,” *Physics Today*, vol. 52, pp. 22–28, May 1999.

[17] M. Dragoman, G. Konstantinidis, A. Kostopoulos, D. Dragoman, D. Neculoiu, R. Buiculescu, R. Plana, F. Coccetti, and H. Hartnagel, “Multiple negative resistances in trenched structures bridged with carbon nanotubes,” *Appl. Phys. Lett.*, vol. 93, no. 4, pp. 043 117–3, Jul 2008.

[18] Y. Wang, K. Kempa, B. Kimball, J. Carlson, G. Benham, W. Li, T. Kempa, J. Rybczynski, A. Herczynski, and Z. Ren, “Receiving and transmitting light-like radio waves: Antenna effects in arrays of aligned carbon nanotubes,” *Appl. Phys. Lett.*, vol. 85, no. 13, pp. 2607 – 2609, Sep. 2004.

[19] P. Burke, “Carbon Nanotube Devices for GHz to THz Applications,” *Proc. of SPIE*, vol. 5593, pp. 52–61, 2003.

[20] G. Slepyan, S. Maksimenko, A. Lakhtakia, O. Yevtushenko, and A. Gusakov, “Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation,” *Phys. Rev. B*, vol. 60, no. 24, pp. 17 136–17 149, Dec 1999.

[21] G. Hanson, “Fundamental Transmitting Properties of Carbon Nanotube Antennas,” *IEEE Trans. Antennas Propagat.*, vol. 53, no. 11, pp. 3426–3435, Nov 2005.

[22] J. Hao and G. Hanson, “Carbon Nanotube Dipoles: Infrared and Optical Antenna Properties,” in *ACES 2006*, Miami, FL, Mar 2006, pp. 353–358.

[23] N. Fichtner, X. Zhou, and P. Russer, “Investigation of carbon nanotube antennas using thin wire integral equations,” *Advances in Radio Science*, vol. 6, pp. 209–211, 2008.

[24] C. Fumeaux, G. D. Boreman, W. Herrmann, H. Rothuizen, and F. K. Kneubühl, “Polarization response of asymmetric-spiral infrared antennas,” *Applied optics*, vol. 36, no. 25, pp. 6485–6490, 1997.

[25] P. Esfandiari, G. Bernstein, P. Fay, W. Porod *et al.*, “Tunable antenna-coupled metal-oxide-metal (MOM) uncooled IR detector,” in *Proc. of SPIE*, vol. 5783, 2005, pp. 471 – 482.

[26] J. A. Bean, B. Tiwari, G. H. Bernstein, P. Fay, and W. Porod, “Thermal infrared detection using dipole antenna-coupled metal-oxide-metal diodes,” *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 27, p. 11, 2009.

[27] B. Tiwari, J. A. Bean, G. Szakmány, G. H. Bernstein, P. Fay, and W. Porod, “Controlled etching and regrowth of tunnel oxide for antenna-coupled metal-oxide-metal diodes,” *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 27, p. 2153, 2009.

[28] J. A. Bean, B. Tiwari, G. Szakmány, G. H. Bernstein, P. Fay, and W. Porod, “Antenna length and polarization response of antenna-coupled MOM diode infrared detectors,” *Infrared Physics & Technology*, 2009.

[29] S. Harrer, S. Strobel, G. Scarpa, G. Abstreiter, M. Tornow, and P. Lugli, “Room temperature nanoimprint lithography using molds fabricated by molecular beam epitaxy,” *IEEE Trans. Nanotechnology*, vol. 7, no. 3, pp. 363–370, 2008.

[30] S. Harrer, S. Strobel, G. Penso Blanco, G. Scarpa, G. Abstreiter, M. Tornow, and P. Lugli, “Technology assessment of a novel high-yield lithographic technique for sub-15-nm direct nanotransfer printing of nanogap electrodes,” *IEEE Trans. Nanotechnology*, vol. 8, no. 6, pp. 662 –670, 2009.

[31] P. Burke, “An RF circuit model for carbon nanotubes,” in *Nanotechnology, 2002. IEEE-NANO 2002. Proceedings of the 2002 2nd IEEE Conference on*, 2002, pp. 393–396.

[32] ——, “An RF circuit model for carbon nanotubes,” *IEEE Trans. Nanotechnology*, vol. 2, no. 1, pp. 55–58, 2003.

[33] N. Fichtner and P. Russer, “On the possibility of nanowire antennas,” in *Microwave Conference, 2006. 36th European*, 2006, pp. 870–873.

[34] P. Burke, “Lüttinger Liquid Theory as a Model of the Gigahertz Electrical Properties of Carbon Nanotubes,” *IEEE Trans. Nanotechnology*, vol. 1, no. 3, pp. 129–144, Sep 2002.

[35] S. Li, Z. Yu, C. Rutherglen, and P. J. Burke, “Electrical properties of 0.4 cm long single-walled carbon nanotubes,” *cond-mat/0408332*, Aug 2004.

[36] C. Rutherglen and P. Burke, “Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes,” *small*, vol. 5, no. 8, pp. 884–906, 2009.

[37] P. Burke, S. Li, and Z. Yu, “Quantitative Theory of Nanowire and Nanotube Antenna Performance,” *Arxiv preprint cond-mat/0408418*, vol. 1, pp. 1 – 16, Aug 2004.

[38] H. Ditlbacher, A. Hohenau, D. Wagner, W. Kreibig, M. Rogers, F. Hofer, F. Aussenegg, and J. Krenn, “Silver Nanowires as Surface Plasmon Resonators,” *Phys. Rev. Lett.*, vol. 95, no. 257403, pp. 1–4, 2005.

[39] A. Attiya, “Lower Frequency Limit of Carbon Nanotube Antenna,” *Progress In Electrom. Research*, vol. 94, pp. 419–433, 2009.

[40] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, “Electric field effect in atomically thin carbon films,” *Science*, vol. 306, no. 5696, pp. 666–669, 2004.

[41] A. K. Geim and K. S. Novoselov, “The rise of graphene,” *Arxiv preprint cond-mat/0702595*, 2007.

[42] A. K. Geim, “Graphene: Status and prospects,” *Science*, vol. 324, no. 5934, pp. 1530–1534, 2009.

[43] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Grigorieva, S. V. Dubonos, and A. A. Firsov, “Two-dimensional gas of massless dirac fermions in graphene,” *Arxiv preprint cond-mat/0509330*, 2005.

[44] S. V. Morozov, K. S. Novoselov, M. I. Katsnelson, F. Schedin, D. C. Elias, J. A. Jaszczak, and A. K. Geim, “Giant intrinsic carrier mobilities in graphene and its bilayer,” *Phys. Rev. Lett.*, vol. 100, no. 1, pp. 16 602–16 605, 2008.

[45] F. Rana, “Graphen Terahertz Plasmon Oscillators,” *arXiv:0710.3556v1 [cond-mat.mes-hall]*, vol. 1, pp. 0–8, Oct 2007.

[46] G. W. Hanson, “Dyadic green’s functions and guided surface waves for a surface conductivity model of graphene,” *Journal of Applied Physics*, vol. 103, no. 6, pp. 064 302–8, Mar. 2008.

[47] J. Moon, D. Curtis, M. Hu, D. Wong, P. Campbell, G. Jernigan, J. L. Tedesco, B. VanMil, R. L. Myers-Ward, C. Eddy Jr *et al.*, “Development toward Wafer-Scale graphene RF electronics,” in *Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, January 11–13, 2010, New Orleans, LA*, Jan 2010, pp. 1–3.