Advantages of 3D Printed Graphene for Sensors/Antennas:

Graphene based materials for passive wireless sensing

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Introduction

Future wireless sensing applications will benefit from high-performance features, advanced diagnostics, connected feedback, networking, low or no power and low cost.

3D printing has emerged as an additive manufacturing technique and enables customized substrate structures that take advantage of material properties (electrical, optical, thermal, mechanical) and potentially with lower cost.

3D printing is broad; it includes a variety of manufacturing processes:

- *powder bed fusion, fused filament, material extrusion, sheet lamination, binder jetting, photopolymerization, digital light processing, stereolithography, directed energy deposition*

Advantages: Materials

Which process is more suitable?

Traditional manufacturing processes suffer from low material utilization, expensive equipment, compacted fabrication steps and design freedom.

There are already efforts underway focused on the use of additive manufacturing for sensors and antennas.

3D printing processes can be started and paused to incorporate other complementary fabrication processes or even to embed sub-components manufactured with more traditional methods.

Printed devices and structures can be fabricated by either embedding a sensor or intrinsically printing the entire device or sensor in a seamless process.

New Materials

3D printing processes take advantage of a variety of materials such as polymers, metals, composites, ceramics and carbon.

Can utilize different materials, to create complex geometric shapes and can merge functional components into a variety of configurations.

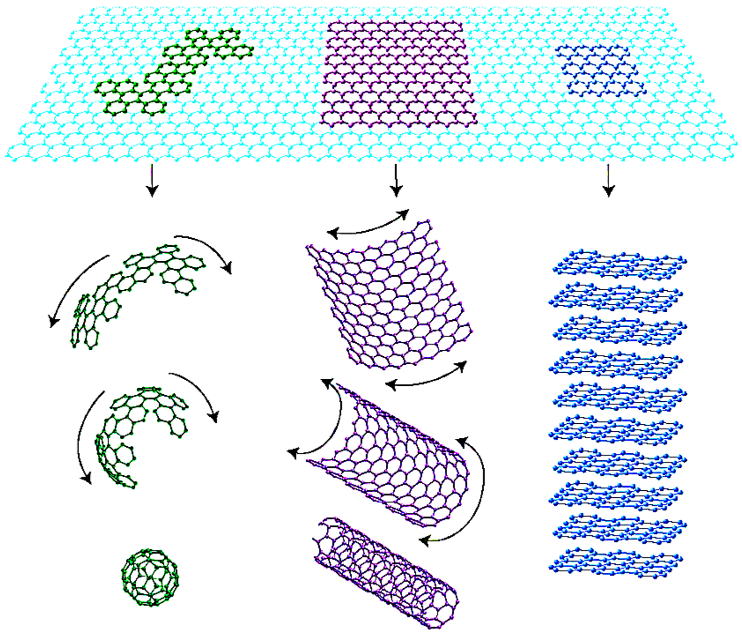
- combine optical, chemical, electronic, electromagnetic, fluidic, thermal and acoustic features

Carbon based materials such as graphene can provide a good alternative because of advantages in material properties (optical, electronic, electrical, thermal and mechanical).

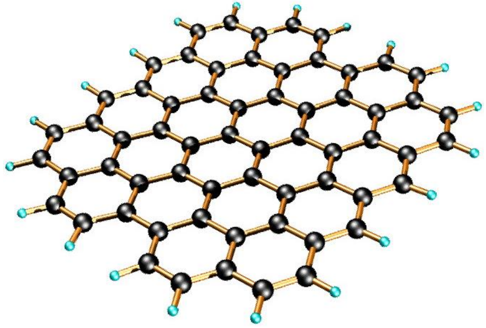
- intrinsic electrical conductivity close to metals
- > 100 stronger than steel

Graphene materials have the potential to be used for passive wireless sensing as sensors, antennas, devices

Graphene



- Graphene is a flat, one atom thick sheet of hexagonally-arranged carbon atoms.
- Basis for C-60 Bucky balls, carbon nanotubes, graphite, carbon composites.
- Excellent photonic, optical, electrical, electronic, thermal mechanical properties.
- Different graphene forms suitable for additive manufacturing.



Graphene Fabrication/Synthesis

The various graphene fabrication/synthesis methods produce different quality and forms of graphene with varying suitability for 3D printing.

- chemical vapor deposition produces high quality graphene
- mechanically exfoliated graphene platelets
- graphene flakes and graphene nanoribbons
- 3D graphene structures and graphene oxide

Graphene-based materials can have tunable properties.

- bilayer graphene stacking order and orientation dramatically affect optical and electronic properties.

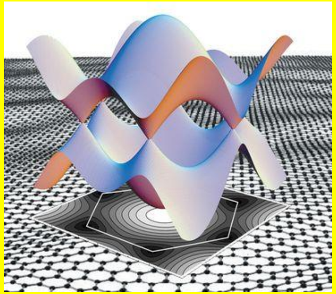
Graphene Properties

Taking advantage of the material properties of graphene-based composites can lead to advances in sensor technology, wireless transmission, energy storage and packaging

Property	Value
Optical transmission	97 - 98%
Electron mobility	> 10^5 cm^2 V^{-1} s^{-1}
Electrical resistivity#	~ $3x10^{-8}$ Ω m
Thermal conductivity	> $2x10^3$ W m^{-1} K^{-1}
Tensile strength*	130 GPa
#Copper *Carbon fiber	~$1.7x10^{-8}$ Ω m ~6 GPa

Graphene Applications

Graphene



Sensors:

Advantages:
Thinnest material - high signal/noise ratios
➔ **Lower detection limits**

Applications:
1) FET - fast, small, low cost
2) SAW
3) MEMS/NEMS

Electronics:

Advantages:
Equal electron and hole mobility.

Applications:
1. Transistors. High mobility. Carbon electronics. Engineered bandgap.
2. THz and RF Antennas
3. RF analog electronics: 100 GHz has already been demonstrated.

fluidics:

Advantages:
One atom thick
➔ **Lowest energy input, high flux**
Crystal structure allows engineering of membranes.

Applications:
1. Liquids: Water desalination. Aquaporin-like functionality.
2. Gases: Target filtration of $CO_2/CH_4/H_2$ and etc.

Thermal management:

Advantages:
Highest thermal conductivity for any material >2000$Wm^{-1}K^{-1}$.

Applications:
1. Thermal management at the nanoscale.
2. Replacement of copper interconnects.

Energy:

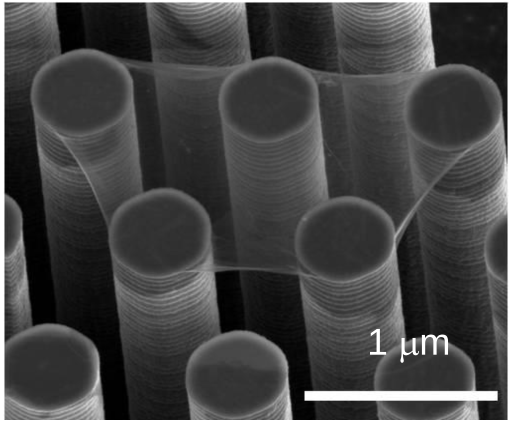
Applications:
1. Anode for Li-ion battery
2. CO_2 harvesting.
3. Hydrogen storage.

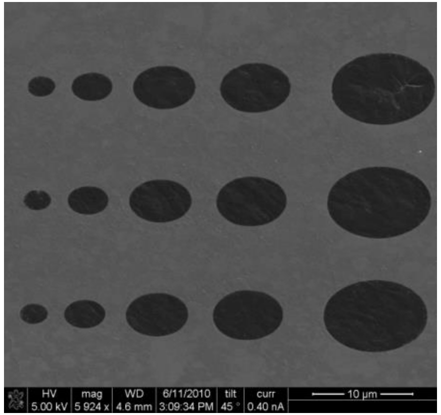
Optics:

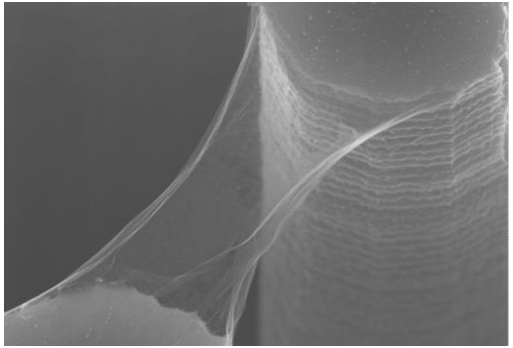
Applications:
1. Transparent, flexible electrode. Substitute to ITO (solar cells, flat panel display, touch screen, OLED).
2. Wide range photodetectors. Reliable detection of 1.55 µm at 10 Gbit/s

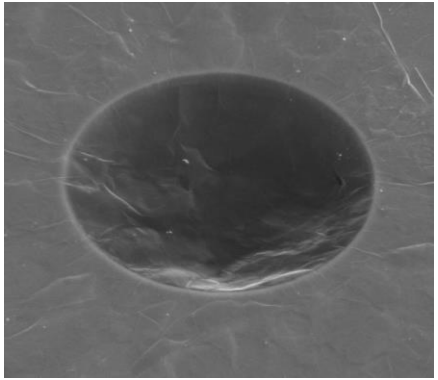
Graphene Membranes and Sheets

Small scale

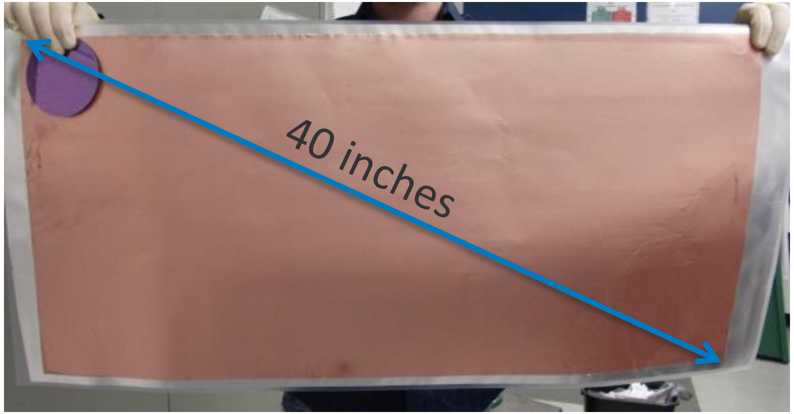






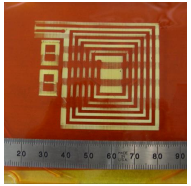


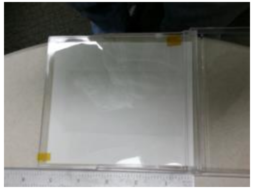
Large scale



Single Layer Graphene Transfer

Kapton	Glass	Mylar	Paper	Graphene Oxide





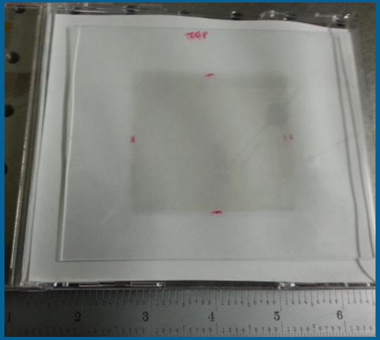
Single layer resistivity ~ 500 Ohms/sq

$1/R_T=N/R$ Conductivity, *1/R*, is directly proportional to the number of layers

$t=(0.997)^N$ Optical transparency, *t*, goes as power of *N*, where *N* is number of layers

Number of layers	Sheet resistance	Optical transmittance
1	~500 Ohms	~98%
4	~150 Ohms	~91%
16	~30 Ohms	~70%

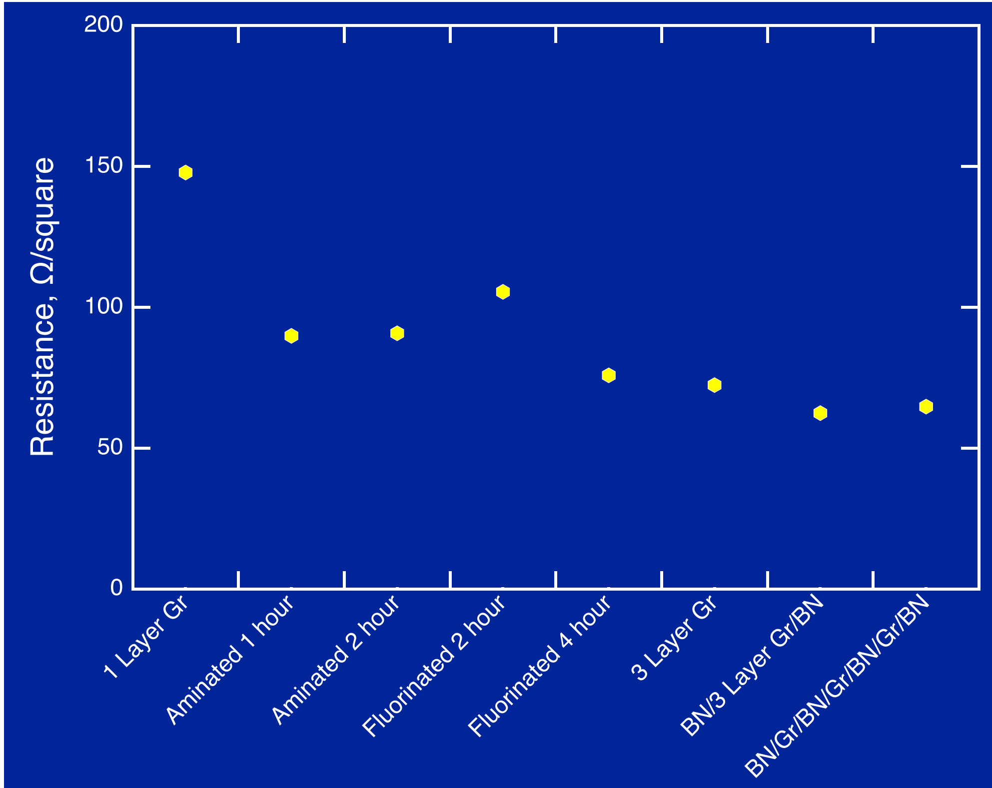
4 layer graphene on glass



Increase conductivity:

- Multilayers
- Physical or chemical doping
- Composites

Graphene Electrical Resistance



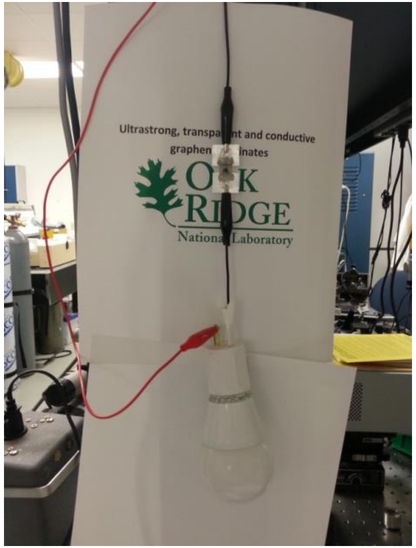
Datskos et al.

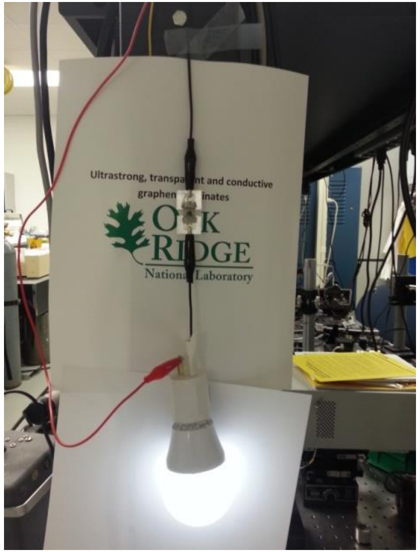
Different configurations of Graphene:

- Multilayers
- Functionalized
- Composites

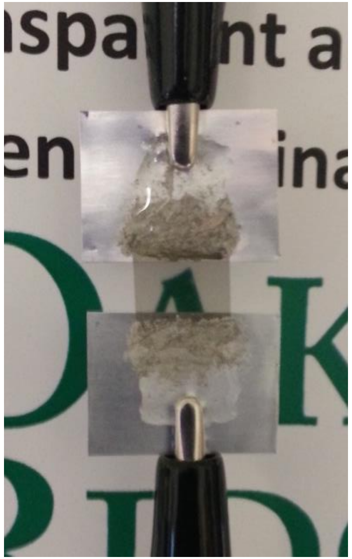
Graphene Composites

Strong – Transparent – Conductive





LED light bulb (~100g) suspended by conductive (PMMA/Graphene)$_{16}$



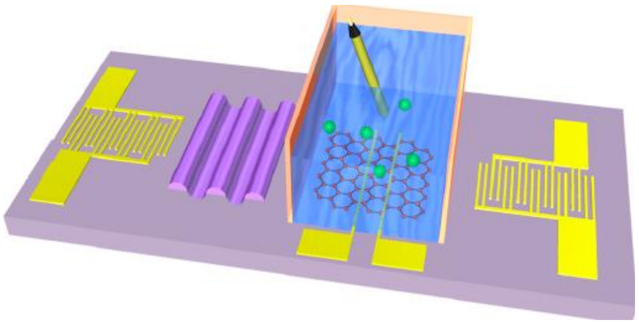
Zoomed in graphene/PMMA area for laminate

Zoomed in graphene/PMMA area for fiber

Graphene Sensors

Graphene based materials have been used in SAW devices

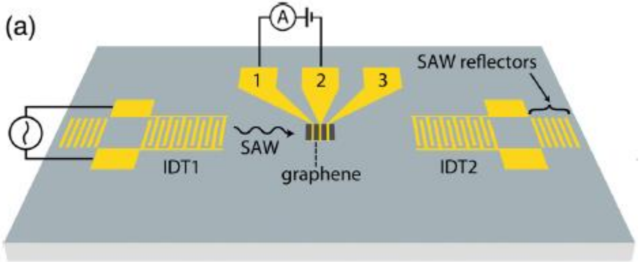
GSAW sensor detects simultaneous both electrical charge and mass loading



[1] Graphene and a SAW to create a graphene surface acoustic wave (GSAW) sensor.

[1] Okuda et al. *ACS Sensors,* **3**, 200 (2018)

Electrical carriers are transported by the SAW and current flows without any external bias



[2]Acoustoelectric current flow in graphene films induced by SAWs on lithium niobate.

[2] Miseikis et al. *Applied Physics Letters,* **100** 133105 (2012)

Graphene in SAWs

Graphene has been used as the active material in SAW, as electrodes and as the sensing medium.

Roshchupkin (2015) used graphene as the electrode material in SAWs.[1]

Mayorov (2014) studied a SAW delay line with a graphene inter-digitized transducer (IDT) that responds to temperature fluctuations and chemical doping. Graphene IDT operates both as an electrode and a sensing medium.[2]

Graphene used as a sensing medium on quartz crystal microbalance to detect volatile organic compounds with high sensitivity.[3]

[1] Roshchupkin et al, "Surface acoustic wave propagation in graphene film," J. Appl. Phys. **118**, 104901 (2015)
[2] Mayorov et al. "Surface acoustic wave generation and detection using graphene interdigitated transducers on lithium niobate." Applied Physics Letters **104**, 083509 (2014)
[3] Yasuhide, et al. "Electrolyte-gated graphene field-effect transistors for detecting pH and protein adsorption." *Nano letters* **9** 2218 (2009)

Graphene as Material for Antennas

Antenna is an important part of the design for wireless systems

There are printable conductive materials:

- *nanoparticles, conductive polymers, carbon nanomaterials*

Metal nanoparticles have high conductivity but compatibility with heat sensitive electronic components is a challenge.

Conductive polymers are cost effective but are limited by chemical and thermal instability. Polymers also lack adequate electrical conductivity.

Carbon nanomaterials – graphene materials – offer attractive advantages in functionality, chemical stability, mechanical flexibility and cost.

Flexible graphene-based conducting materials open up printing of conformal antennas.

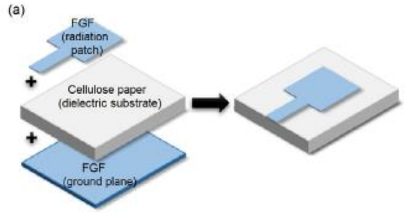
Printed Graphene Antennas

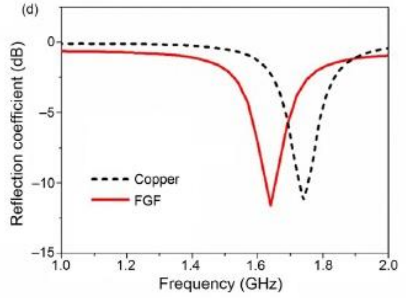
The carbon allotrope graphene is very promising for use in wireless communication - electrical, electronic, optical, thermal and mechanical properties.

Unprocessed Graphene monolayer films have high sheet resistance which limits applications in wireless sensors such as antennas and other passive components.

But… using doping, composites, or multilayer graphene films leads to significantly high electrical conductivity achieving values $>10^7$ S/m.

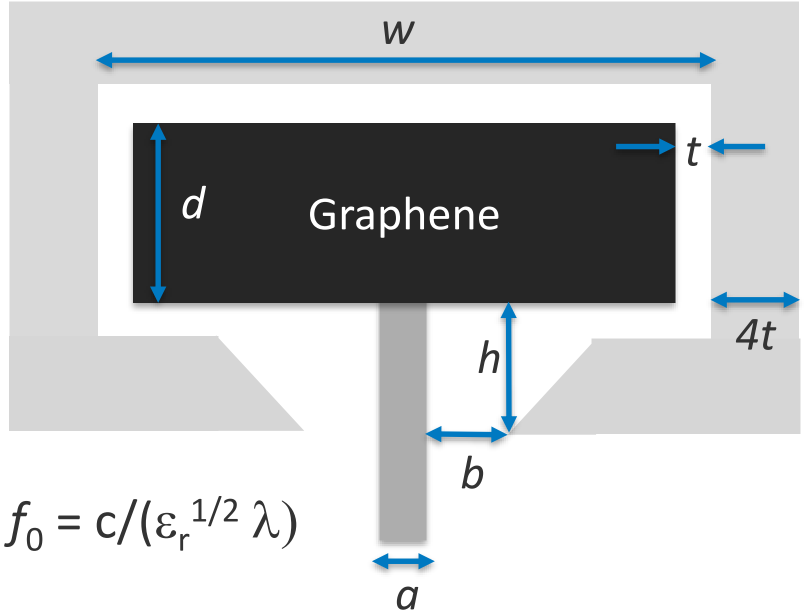
Can be used to fabricate flexible sensors. For example Tang et al. fabricated a 1.63 GHz rectangular microstrip patch antenna on a paper substrate.#





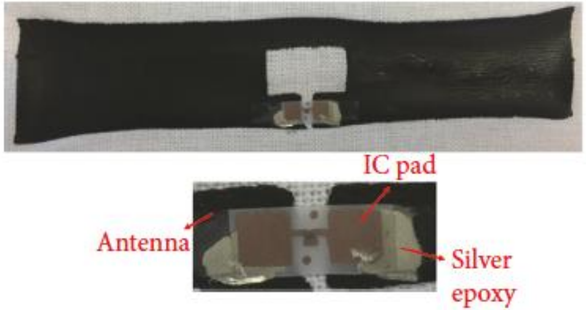
Tang et al. "Highly sensitive wearable sensor based on a flexible multi-layer graphene film antenna." *Science Bulletin* **63**, 574 (2018)

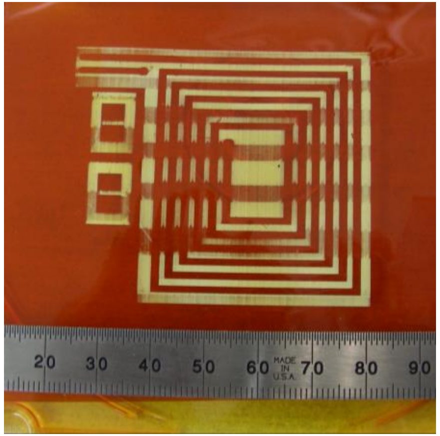
Printed Graphene Patch Antennas



$f_0 = c/(\varepsilon_r^{1/2}\,\lambda)$

He et al. *International Journal of Antennas and Propagation* 2017 (2017)

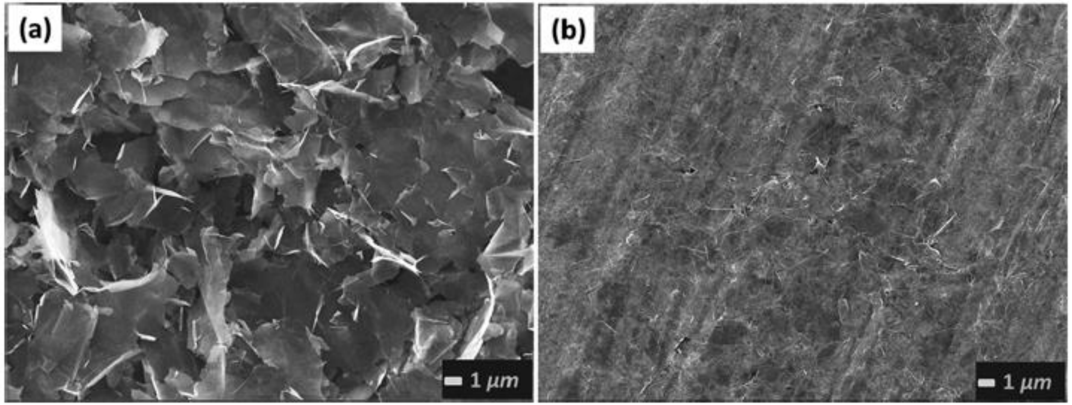




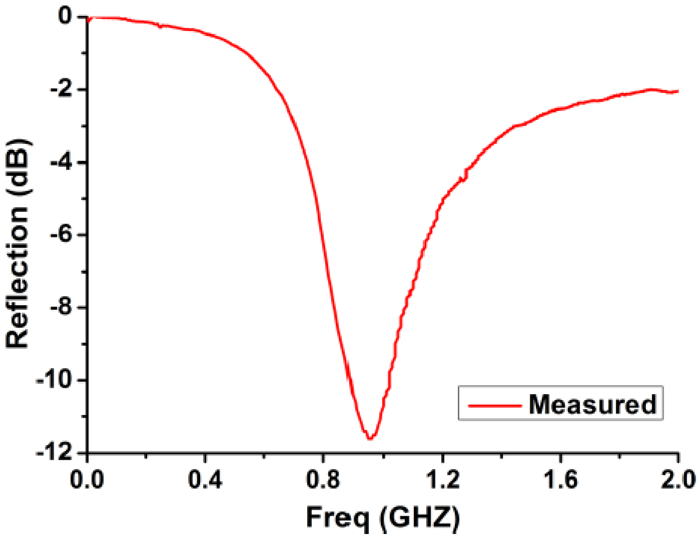
Graphene antenna on Kapton

Datskos (2015)

RF Graphene Laminate Antenna



SEM images of printed graphene laminates.[1]



[1] Huang et al. (2015) "Binder-free highly conductive graphene laminate for low cost printed radio frequency applications." *Applied Physics Letters* **106**, 203105 (2015)

Conclusions

By using graphene materials with functional properties, the capabilities of 3D printing can be expanded to high performance, low cost sensors and antennas

Taking advantage of additive manufacturing approaches and using proper materials can provide a path for the next generation devices, energy storage and packaging.

Because of the electrical, electronic, optical, thermal and mechanical properties of graphene based materials there is the potential for advances in sensor technology, wireless transmission.

Graphene nanocomposites greatly improve 3D printed structures and when graphene nanoplatelets are added to polymers it results in more electrically conductive materials with improved thermal conductivity and higher mechanical strength.

Thank you

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