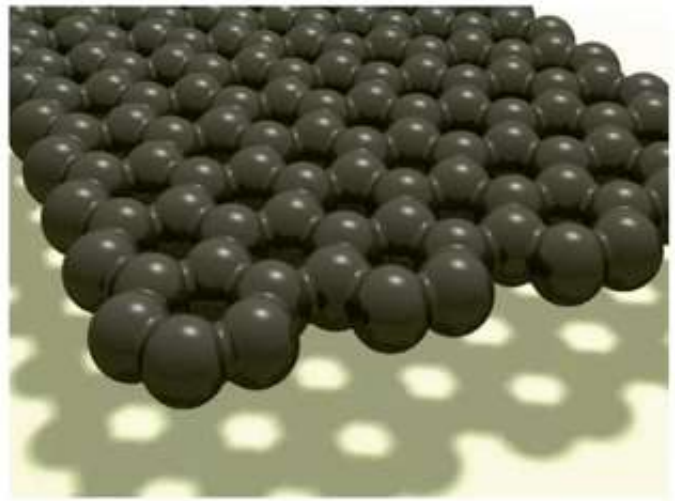
Graphene inks are a promising new entrant

- Considerably cheaper than Ag/Cu ink
- Does not form insulating oxide film like Cu
- No need of sintering graphene ink after printing
  - Can be used to print on **plastic and paper substrates**
- Non-toxic and strong dispersability
- Flexible, robust and crease resistant
- Compatible with all current printing methods
- Graphene inks lose little conductivity when folded



Source: Taghioskoui, M. Trends in graphene research. Materials Today 12, 34-37(2009); Monie, S. Developments in conductive inks. *Industrial specialty printing*. (2010)

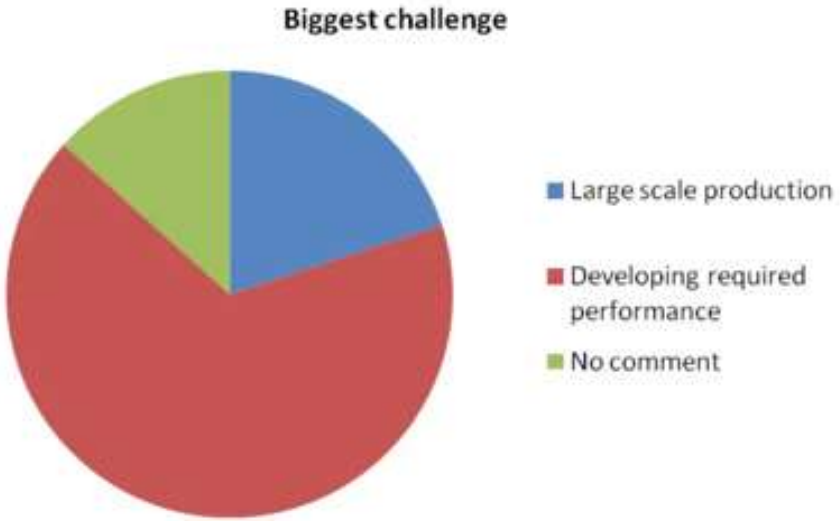
Challenges for commercialization

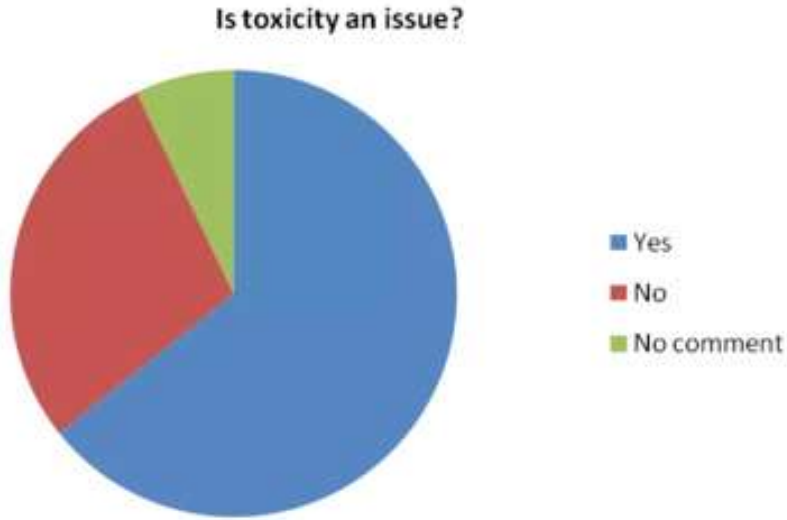
- **Poor homogeneity of inks**: random mix of few single layers and stacks of graphite adversely affect the quality of film deposited

- **Small flake size**: Presence of large number of interflake barriers brings down conductivity significantly

- **Optimum ink formulation**: Achieving required adhesion to the substrate; ensure cohesion without compromising conductivity

Survey results (3/3)



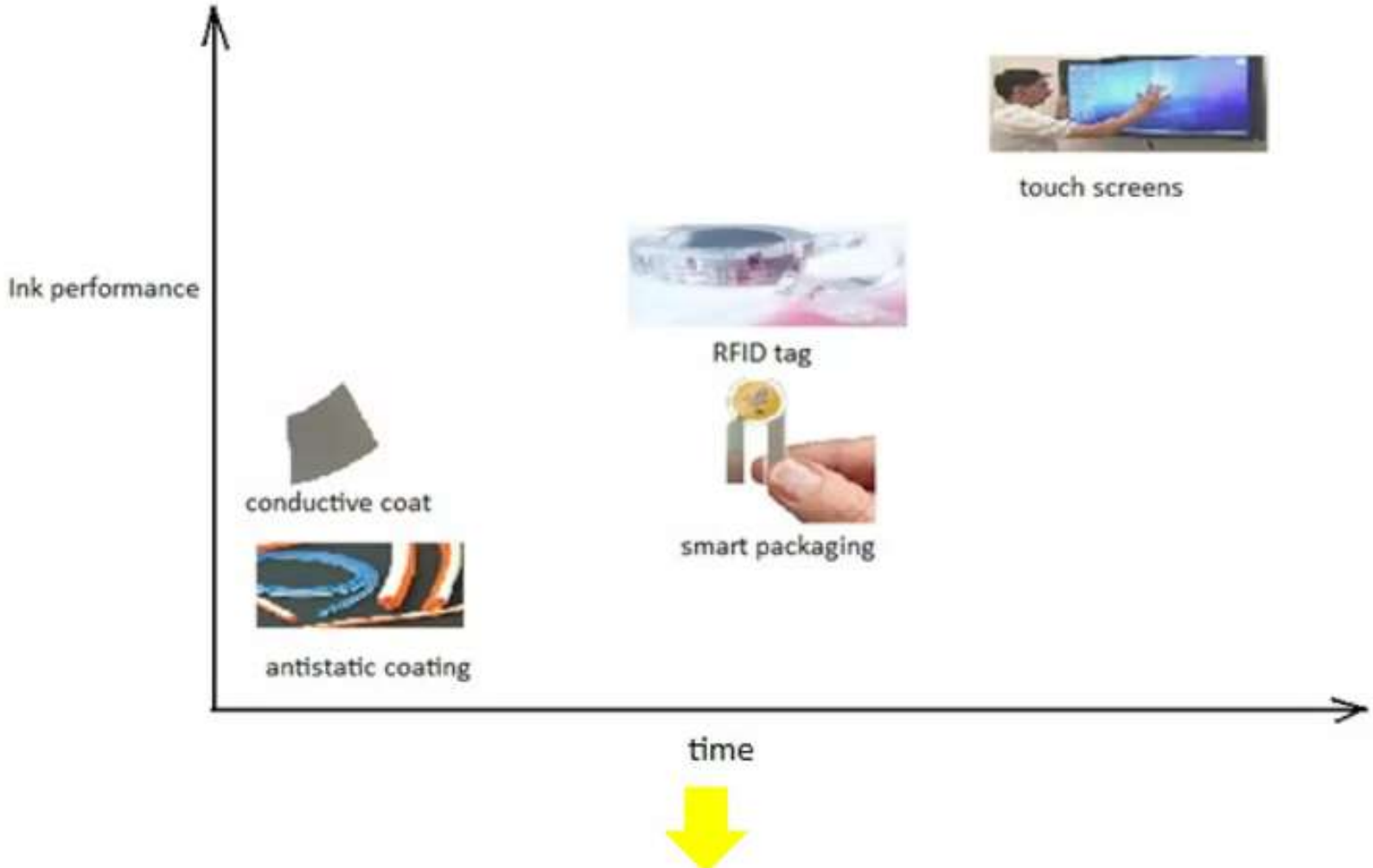


- Larger flake size
- Greater percentage of monolayer graphene

- Graphite oxide induces cytotoxicity and apoptosis in human lung cells
- Multiwall CNTs longer than 20 μm produce harmful carcinogenic effects similar to asbestos
- Toxicity standards need to be established

Source:Vallabani, N. V. et al. Toxicity of Graphene in Normal Human Lung Cells (BEAS-2B). Journal of Biomedical Nanotechnology.7(1),106-107.(2011);
Poland, C. et. al. Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study. Nature Nanotechnology, 3(7):423–428 (2008).

Roadmap of applications



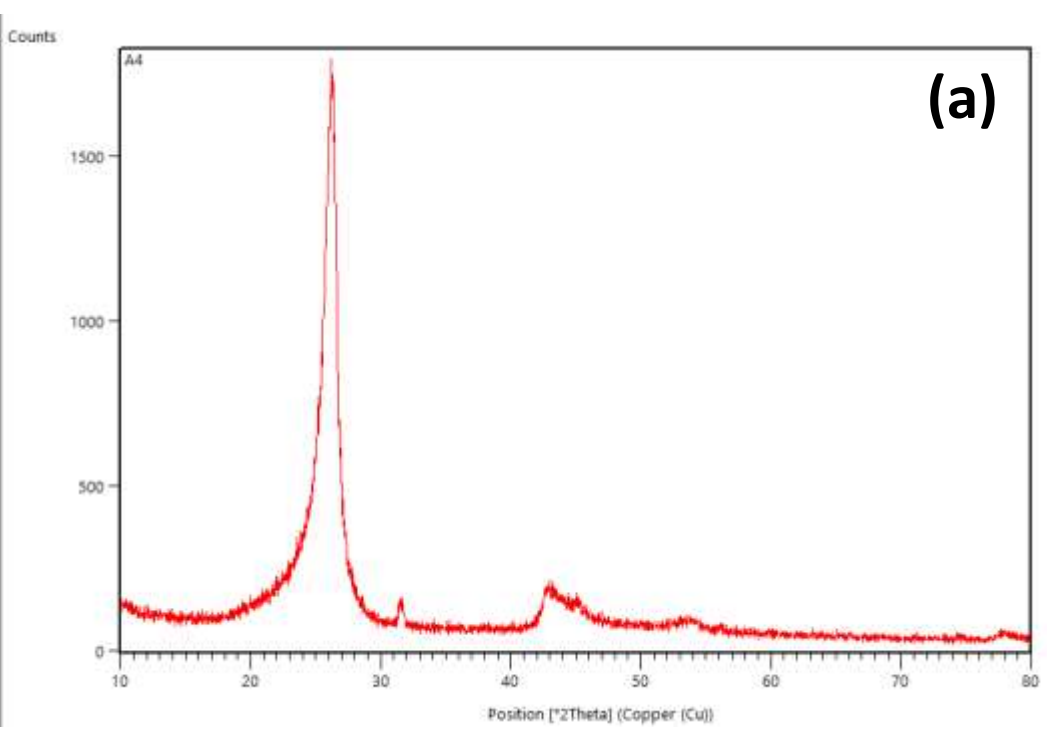
Graphene inks are likely to enter the market in stages starting from low cost low functionality applications

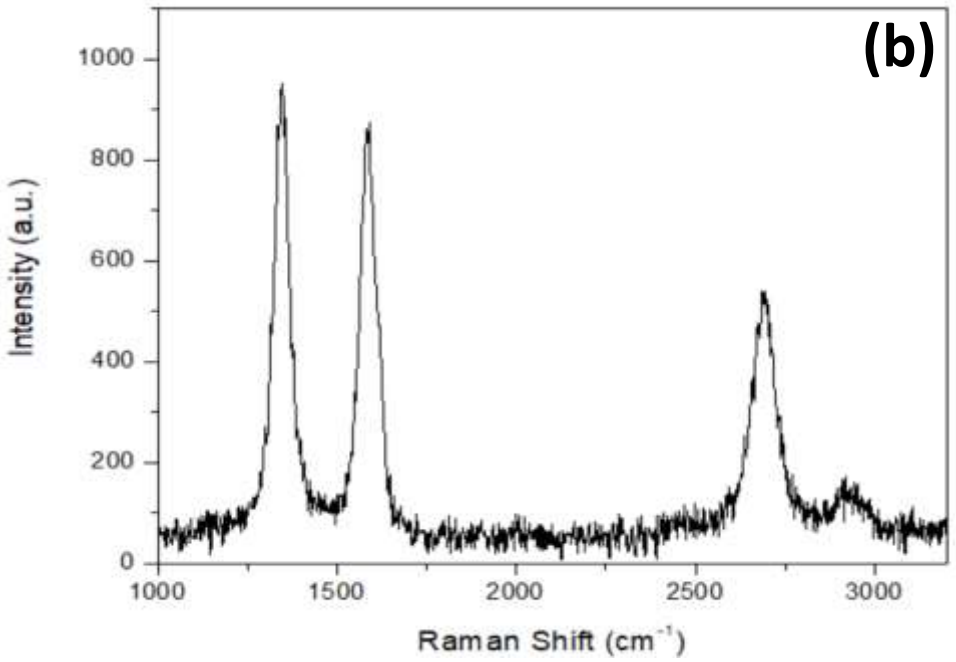
SWOT Analysis

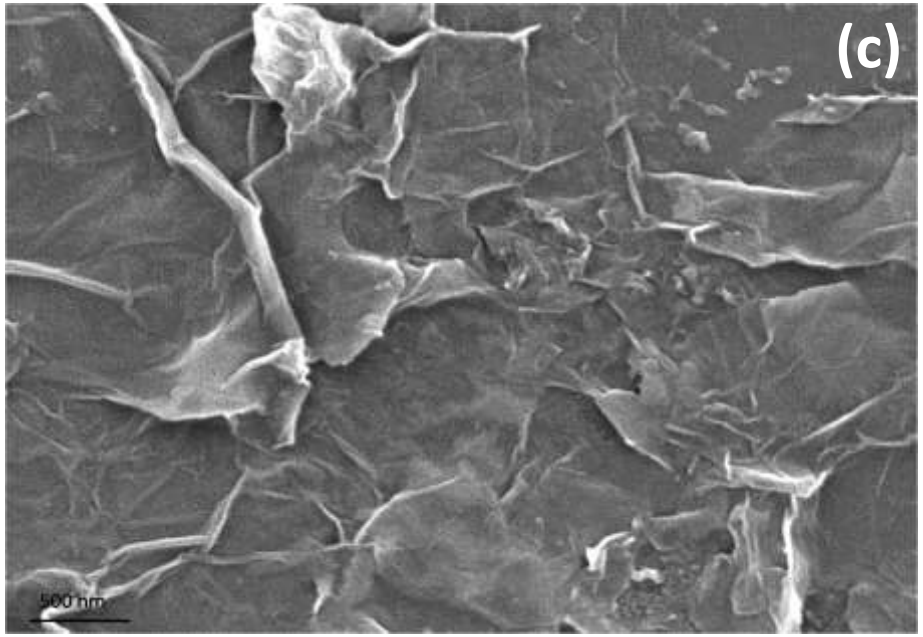
Strengths	Weaknesses
•Low cost •Reasonable conductivity (>1000 ohms/sq) •Good transparency (~90%) •Flexibility •Abundance and scalability •Compatible with current printing technologies •Sinter free curing allows paper/PET substrate	•Interflake barriers lower conductivity •Lack of high % of monolayer graphene •Technical challenges with ink formulation •Conductivity insufficient for high current applications eg. OPV, solar cells
Opportunities	**Threats**
•Low cost low functionality applications •Silver inks getting expensive •Emerging applications: RFID tags, smart packaging •Low end ITO replacement in near future •Flexible electronics •Ink patent landscape not mature: scope for early mover advantage	•Copper inks improving in performance and cheaper than silver •Competing technologies may capture market share if inks take long to reach required performance •Toxicity issues need to be addressed •Durability still unproven

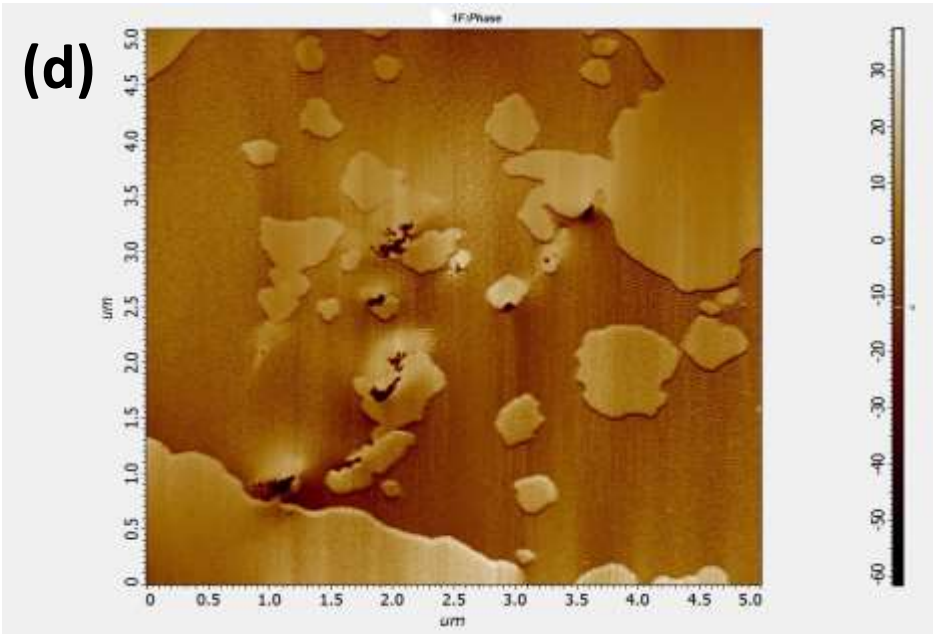
Comparison of CVD graphene and inks

CVD method	**Solution-based exfoliation**
High quality graphene	Low quality graphene
Mostly monolayer sheets	Multi-layer sheets
Sheet size of few cm	Sheet size of few microns
Expensive	Cheap
Replacement of ITO	Electrostatic dissipation, conductive coatings









(a): XRD
(b): Raman Spectra
(c): FESEM
(d): AFM