Lead-Free Universal Solders for Optical and MEMS Packaging

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OUTLINE

- Introduction
- Universal Solder Fabrication
- Microstructure
- Direct Bond Strengths on Oxide, Carbide, Nitride, etc.
- Contact Resistance to Semiconductors
- Potential Applications in Optical and MEMS Devices
- Summary

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Construction of Modern Electronic and Optical Devices

- **Computers, wireless handsets, telecom networks**
- **Reliable bonding of dissimilar materials --- one of the essential and often critical fabrication steps**
- **Electronic devices/assemblies typically contain**
  - **Base semiconductors (Si, GaAs, GaN, SiC, doped diamond)**
  - **Dielectric layers (SiO_2, Ta_2O_5, Si_3N_4)**
  - **Diffusion barriers (TiN, TaN)**
  - **Heat sinks (AlN, Al, Cu, diamond)**
- **Optical divices/assemblies**
  - **Telecom optical fiber (SiO_2)**
  - **Photoconductors/phosphors (ZnSe, ZnS), optical windows (MgF_2)**
- **For convenience, simplicity & reliability --- direct solder bonding at low temp. is desirable**
- **Surfaces of these materials --- difficult to wet and bond with solders**

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METALLIZATION ISSUES

- **Solder bonding of non-wettable surfaces conventionally done by using:**
  - **Multilayer metallization**

    e.g., Ti/Pt/Au
  - **Electroless Ni-P coating**

- **Disadvantages of intermediate metallization:**
  - **Multiple interfaces & associated reliability issues**
  - **Possibly poor chemical bond at interface**
  - **Complexity and cost**

=> Desirable to omit metallization step(s)

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APPROACHES FOR UNIVERSAL SOLDERS

- **Solders do not wet oxides, carbides, nitrides etc. -- no chemical reaction**
- **Approach to enable solder bonding on such non-wettable surfaces:**
  - **Rare earth elements: most reactive of all elements in periodic table**
  - **We incorporated a few wt% of rare earths (Lu, Er, Ce) into host solders**
- **Result: The RE-doped solders bond to essentially all inorganic surfaces --- named "Universal Solder"**
- **Presented at TMS 2000 Mtg., Published in APL 78, 2976 (2001), APL 80, 398 (2002).**

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RE-doped AuSn Solder: *78.4Au-19.6Sn-2Lu*

- Au-Sn eutectic solders widely used in optical packaging - due to high m.p. & creep-resistance
- Incorporated reactive metal (Lutetium) into AuSn solder system: 80Au-20Sn + 2wt% Lu
- Creep resistance expected to be comparable to AuSn eutectic
- M.P. ~283°C (similar to AuSn eutectic)
- This solder bonds well on SiO_2 optical fiber without metallization:

  Bond Shear Strength >17 MPa (2.5 ksi)

  Fiber stress = 1088 MPa (158 ksi)
- Tendency for easy oxidation may require care during soldering (e.g. short soldering time, inert atmosphere)
  - however successful hand-soldering in air, without any flux demonstrated

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RE-doped SnAg Solder: *Sn-3.4Ag-2.5Lu*

- Sn-3.5wt%Ag eutectic (m.p. ~220ºC) is the primary Pb-free solder to replace traditional Pb-Sn solders
  - significantly higher creep-resistance and fatigue resistance than Pb-Sn eutectic

- Sn-3.5Ag + 2.5 wt% Lu or Er

- Bonds to essentially all inorganic surfaces similarly as Au-Sn-RE, but is more ductile and can accommodate stresses

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Solder Bonding Experiments

- Various substrates heated on hot plate to ~70^{o}C higher than solder M.P. (to ~290^{o}C for the RE-doped Sn-Ag eutectic, and to ~350^{o}C for the RE-doped Au-Sn eutectic)
- Hand soldered using a soldering gun

  --- In air, with no flux

  --- 1 – 10 seconds

- Ni (or cu) wire attached by universal solder bonding onto oxide, nitride, carbide, fluoride, diamond, semiconductor, and other substrates --- for shear pull test to determine bond strength
- Powerful bonding obtained (shear pull test --- bond strengths of greater than ~2000 psi)

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Possible Mechanism for Universal Solder Bonding

- Rare-earth containing compounds (oxides,carbides, nitrides, fluorides) are very stable --- with large negative ΔH_f (heat of formation)

ΔH_f (SiO_2) = -195 Kcal/mole at ~298°K

vs ΔH_f (Lu_2O_3) = -282 Kcal/mole at ~298°K

ΔH_f (Er_2O_3) = -290 Kcal/mole at ~298°K

- Lu (in molten solder) + SiO_2 (Opt. Fiber) → Lu_2O_3 + Si
- Chemical bonding reaction at solder-substrate interface

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Reliability Issues

- **Reactive, easily-oxidizable rare-earth is stored in micron-scale intermetallic islands**
    - **e.g., Au_4Lu islands embedded in Au-rich matrix in Au-Sn-Lu solder**
    - **Sn_3Lu islands in the case of Sn-Ag-Lu solder**
- **During soldering, the islands dissolve and allow the RE elements diffuse to the interface for bonding**
- **On solidification after soldering, the RE is re-stored in the islands**
- ***This mechanism of storage as stable intermetallics --- desirable for reliability***

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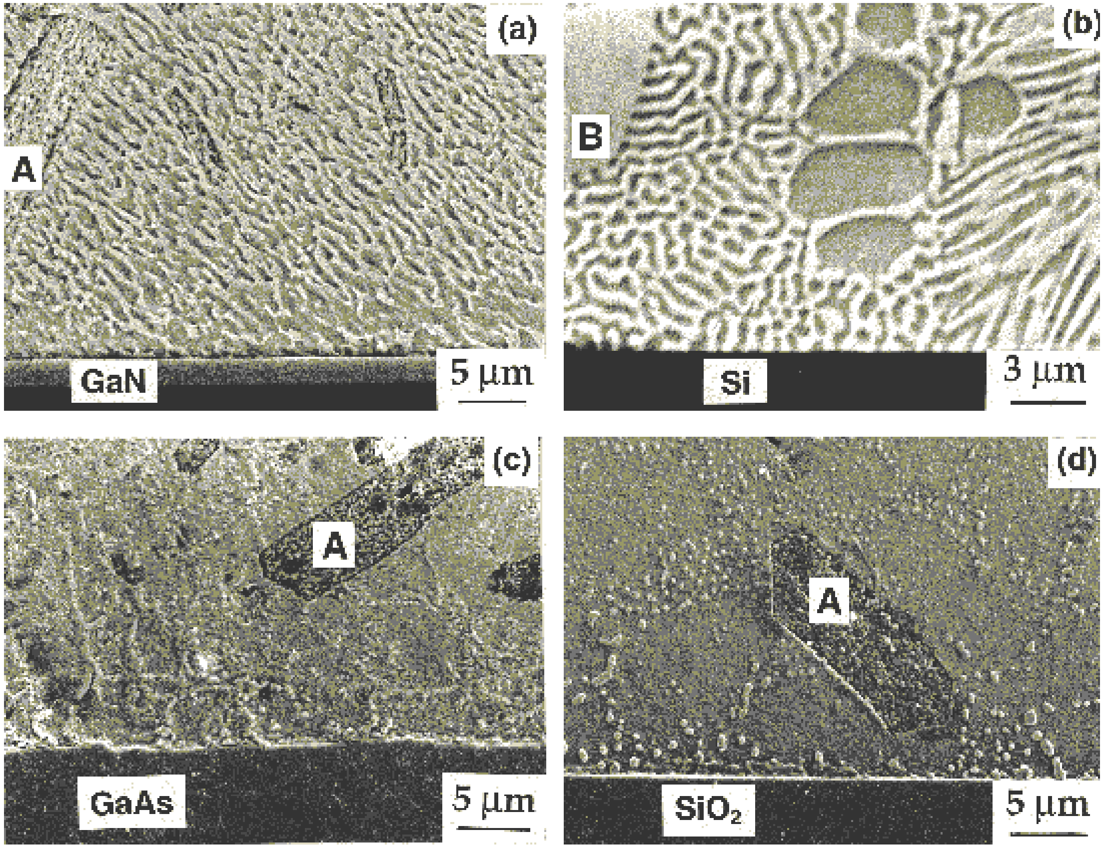
CROSS-SECTIONAL MICROSTRUCTURES (SEM)

(a) SnAgLu/GaN **(b) AuSnLu/Si**



(c) SnAgLu/GaAs **(d) SnAgLu/SiO_2**

A: Sn_3Lu
B: Au_4Lu

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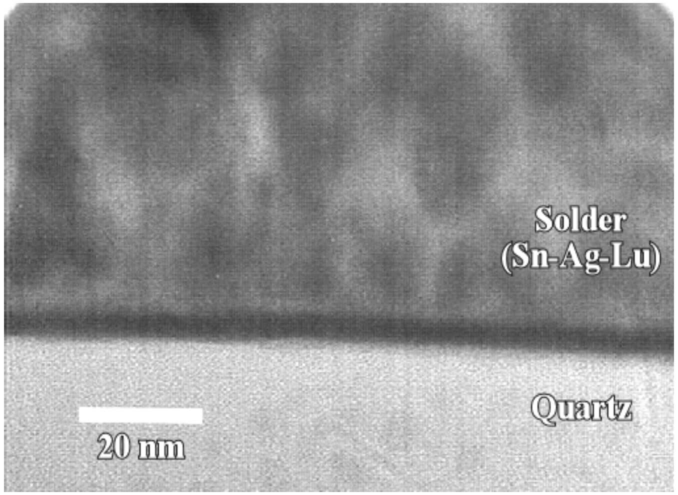
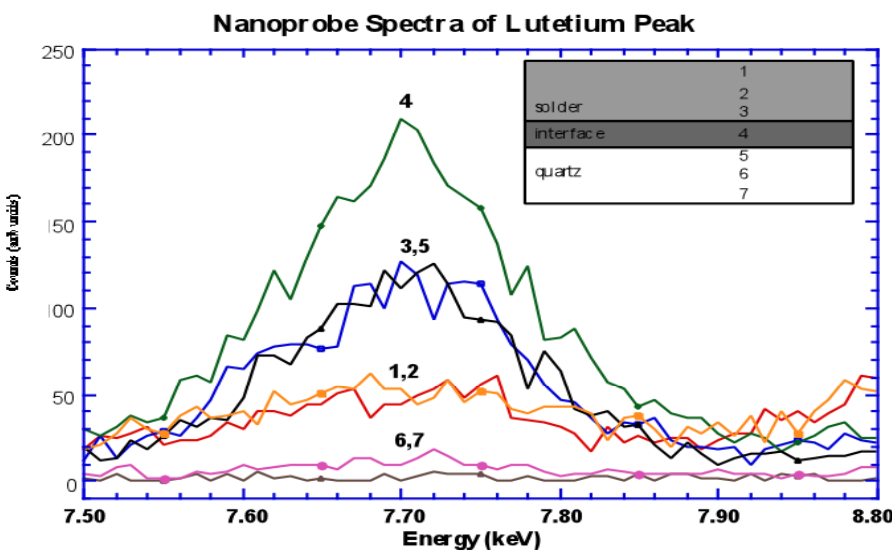
TEM and EDX Nanoprobe Spectra of SnAgLu/Quartz Interface



? *Evidence of nanometer-sized bonding layer*



? *Evidence of Lutetium segregation at the interface*

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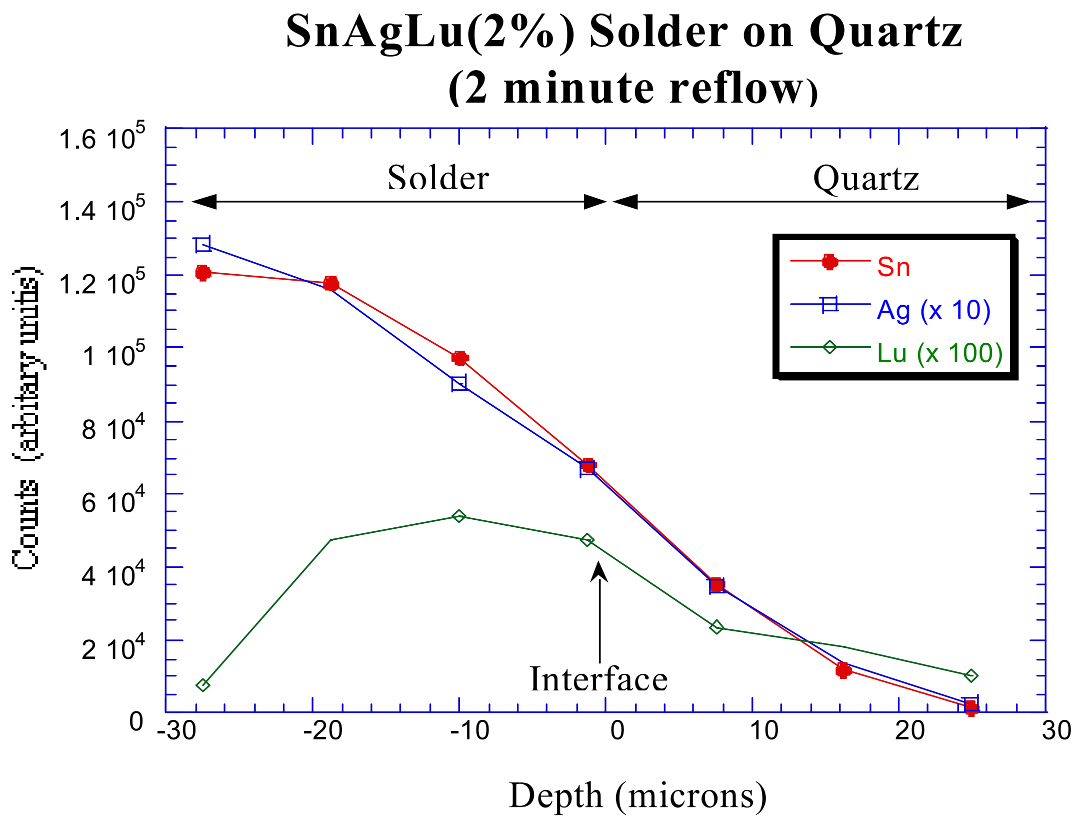
XPS (X-ray Photoelectron Spectroscopy) Depth Profile



=> Evidence of micron-scale buildup of Lu at solder/substrate interface

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Electrical Contacts to Semiconductors

- There is a need to provide electrical conduction paths onto semiconductor surfaces
- To carry out package bonding (flip chip, wire bond, metallization leads) for connection to different interconnection levels or to other semiconductor devices
- Ohmic contacts with low resistivity desirable
- Multi-layer metallizations and high-temp. anneal (e.g., 900^{o}C) often required to achieve low contact resistance
- Direct solder bonding at low temp. (~250 – 300^{o}C) on semiconductors without complicated multi-layer metallizations, without high temp. anneal --- desirable

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Univ. Solder – Semiconductor Contact Resistance Measurement

- **RE-doped Sn-Ag eutectic (with ~2.5% Lu) was used to make direct solder bonding to semiconductor surfaces using soldering gun in air.**
- **Four point I-V curves and three point I-V curves measured --- differential contact resistance evaluated [*see Jin, et al, APL 54, 2605 (1989), APL 56, 186 (1990*)]**
- **Semiconductors studied**

  --- n-type (0001) GaN, carrier conc.~$1.5x10^{18}$ Si/cm^3

  --- n-type (1120) SiC, carrier conc.~$5x10^{17}$ N/cm^3

  --- n-type (100) Si, carrier conc.~ $1x10^{18}$ P/cm^3

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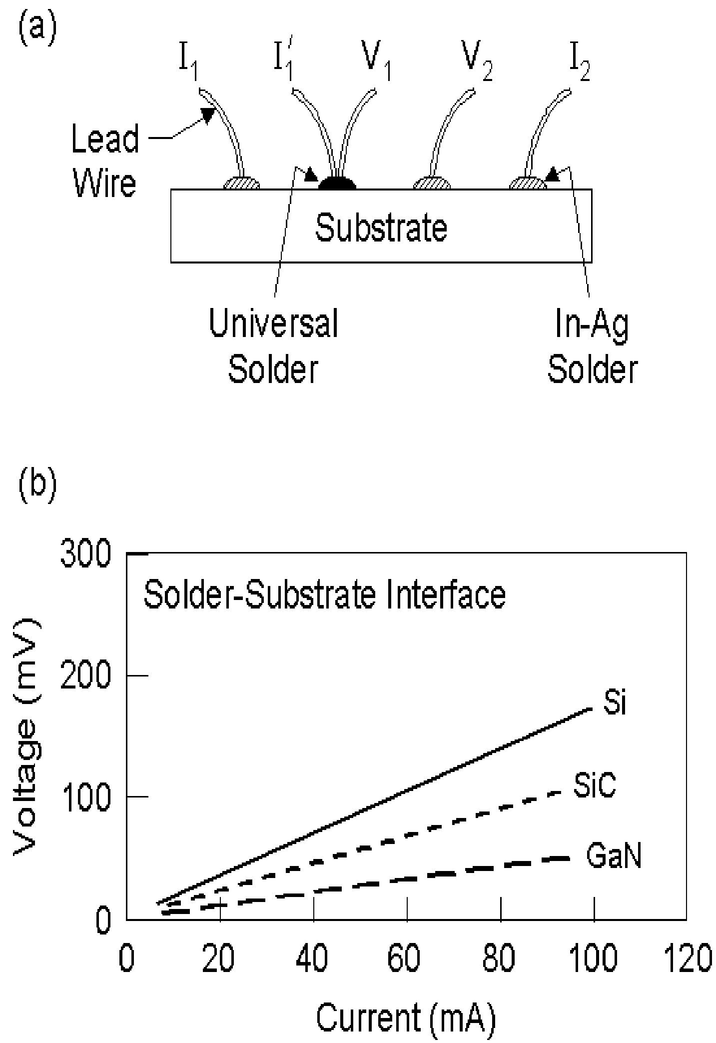
CONTACT RESISTANCE MEASUREMENT



Contact resistivity: ~0.01-0.02 ohm-cm^2 for SnAgLu

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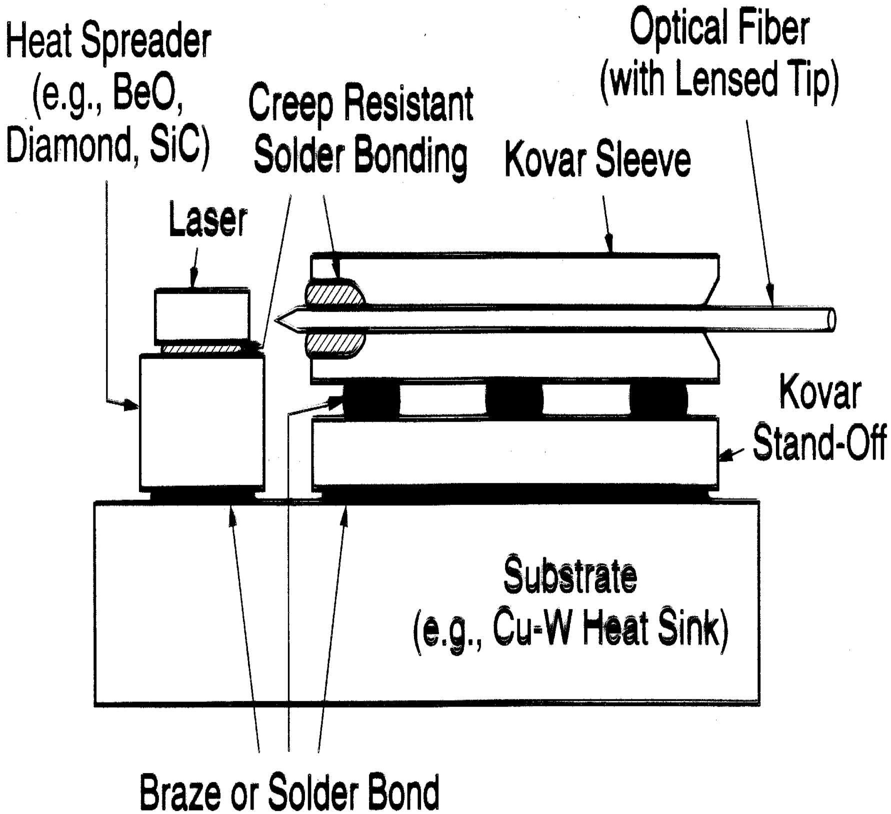
Typical Device Package Requiring Dimensionally-Stable



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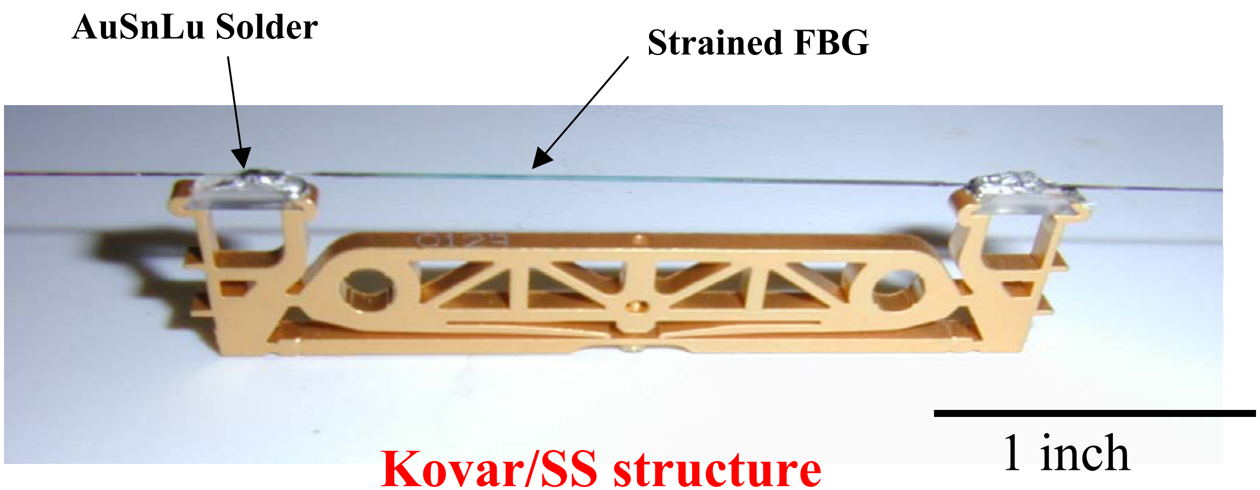
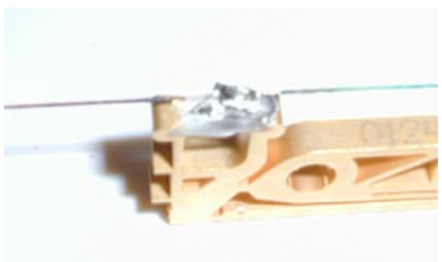
Bonding of Strained FBG for Temperature-Compensation

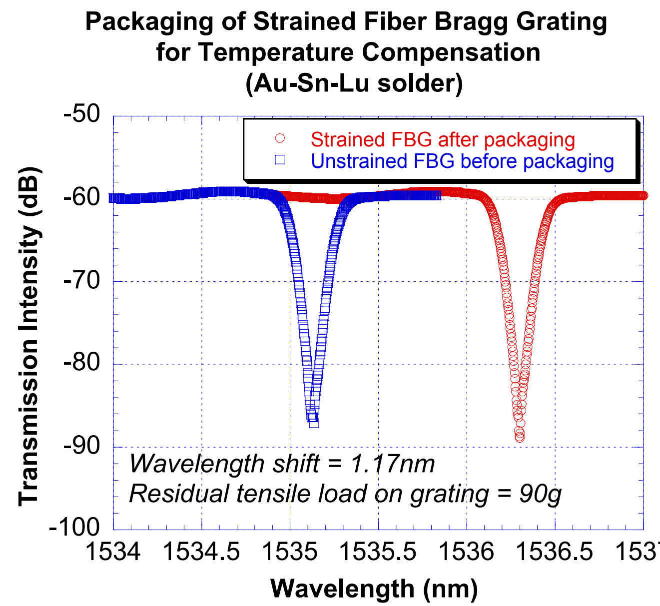


Kovar/SS structure



$$\lambda = 2n_{eff}\Lambda$$

λ	- *Bragg wavelength*
n_{eff}	- *Eff. Refractive index*
Λ	- *Grating periodicity*



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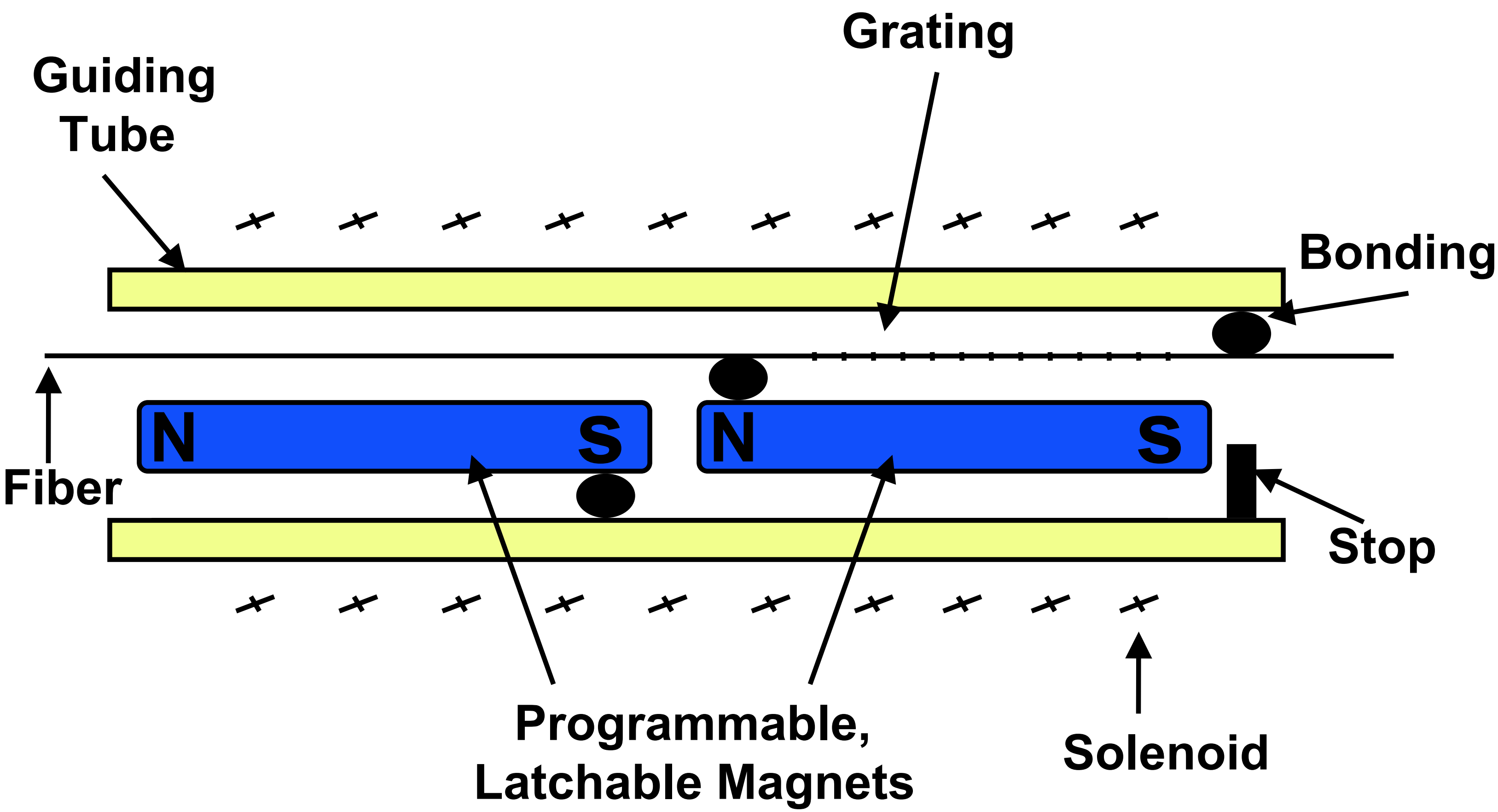
Tunable Fiber Gratings



- Jin et al., Electronics Lett. 34, 1 (1998).

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Need for Miniature Vacuum Tubes

- Modern communications industry (f>~GHz; radio, TV, microwave comm.)--- born with gridded vacuum tube amplifiers decades ago
- Drawbacks --- 1. Bulky,   2. Uses hot cathode (can not be close enough to the control grid for higher frequency)
- Solid state transistors --- allowed miniaturization, replaced most applications except radar/warfare, space tech.
- However, fundamental drawbacks of solid state amplifiers

  -- Electrons move ~1000 times slower in solid than in vacuum, with collisions and unwanted heat generation

  -- Low power --- For 100~500 watt needed in microwave base station (for wireless comm.), many transistors in parallel with complex circuits, bulky thermal management

Can we achieve the best of both technologies?

-- For size miniaturization & high microwave power

-- Combine Nano (cold cathode with nanotubes) + MEMS !

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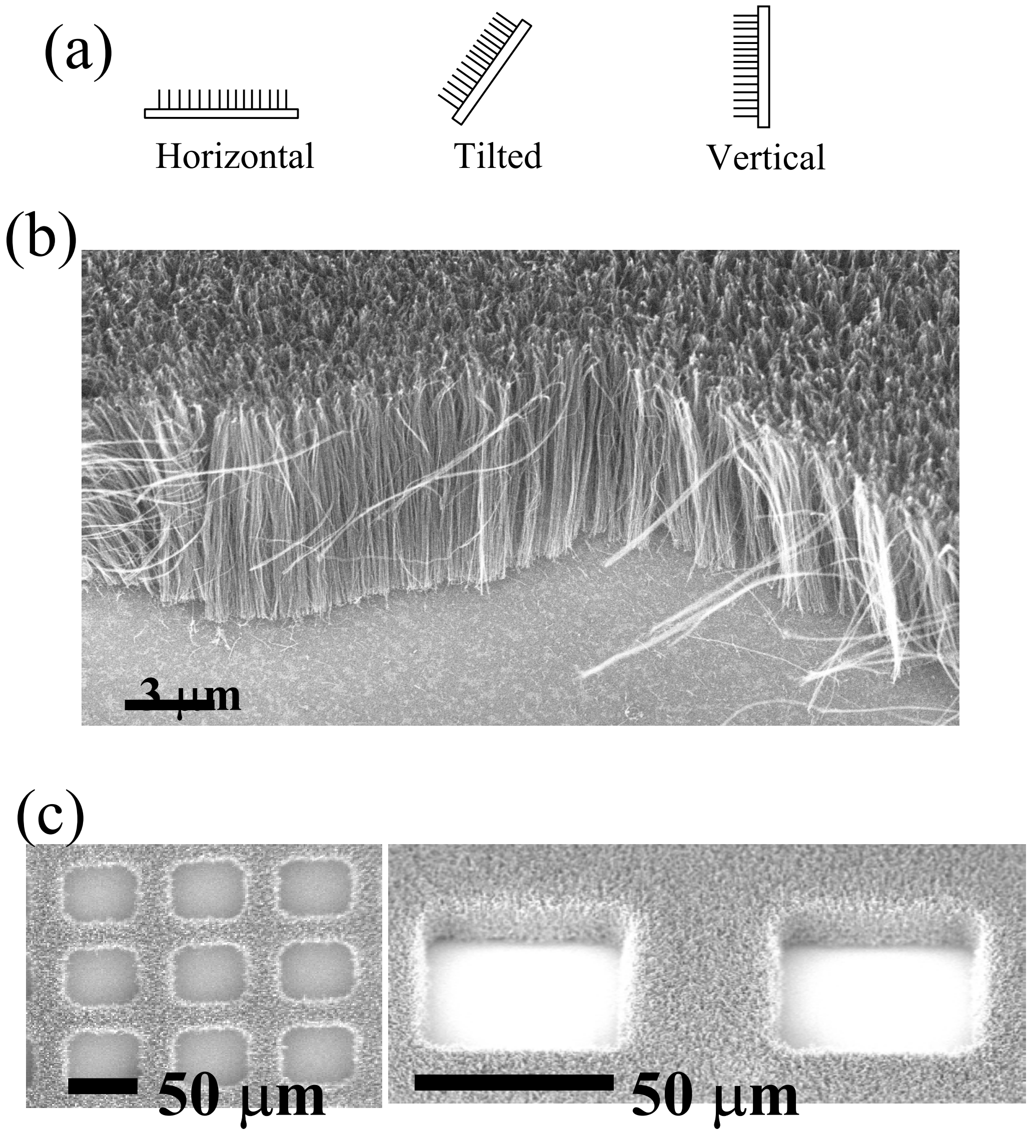
Aligned Carbon Nanotubes by MPE-CVD



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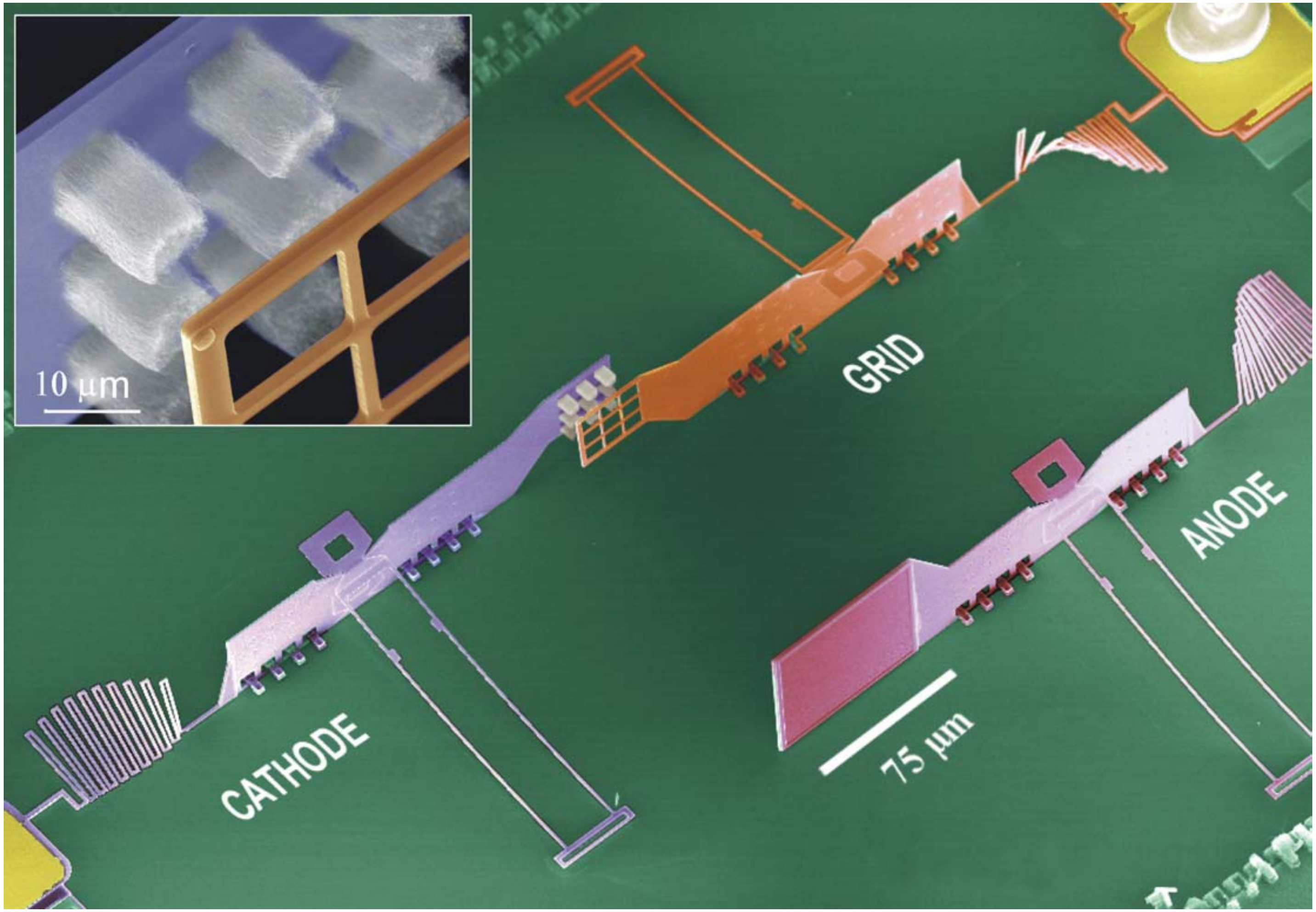
MEMS-Based Micro Vacuum Triode Using Carbon Nanotube Cold Cathode



• Bower, et al., in APL 76, 3820 (May 2002), also Bower, et al., in IEEE Trans. Electron Devices 49, 1478 (August 2001).

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Summary

- Universal solders containing rare earth elements fabricated.
- Direct and powerful bonding to oxide, carbide, nitride, fluoride, diamond, Si, GaAs, etc. demonstrated by low temp. (250 – 300°C), flux-less soldering.
- Some soldering methodologies discussed.
- Potentially useful for
  -- Bonding of semiconductor components (dielectric layers, diffusion barriers, heat sinks), direct Ohmic contacts to semiconductor surfaces, SiO_2 – Si hermetic seal
  -- Assembly/packaging of optical and MEMS devices

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