Applications of FTIR Spectroscopy to Advanced Packaging

John JH Reche
945 E. Verde Lane, Tempe, AZ 85284
jjcreche@wafer-bumping.com

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Outline

- Brief review of FTIR (Fourier Transform Infrared) spectroscopy
  - How does it work?
  - Data acquisition techniques
  - What information do we get?
  - Interpretation of the data

- Applications to semiconductor
  - Polymer processing
  - Identification of polymers
  - Plasma processing
  - Sputtering
  - Failure analysis
  - Quality control
    - Incoming inspection
Harmonic oscillator model

- IR radiation interacts with molecules
- Bonds between atoms vibrate when absorbing specific wavelength
  - Bonds absorb energy at some characteristic frequency of their functional groups
  - To absorb IR energy, the vibration of a bond must induce a net change in dipole moment as a result of vibrational or rotational motion
  - Simple harmonic oscillator model
  - Vibrations can be subdivided into two classes, depending on whether the bond length or angle is changing
    - Stretching (symmetric and asymmetric)
    - Bending (scissoring, rocking, wagging and twisting)
Examples of IR induced vibrational modes

- Energies associated with the vibrational found between 4000 cm\(^{-1}\) and 650 cm\(^{-1}\)
- Rotational energies are generally much smaller (below 300 cm\(^{-1}\))
Preferred FTIR equipment for packaging

- Covers IR spectra from 4500 cm\(^{-1}\) to 650 cm\(^{-1}\)
- ATR (Attenuated Total Reflectance)
  - Sample spatial resolution < 150 µm
- Micro ATR microscope Objective
  - Sample spatial resolution ~ 25 µm
- Reflectance microscope objective
  - Diffraction limited by microscope objective
- FTIR mapping
  - Can spatially map absorbance over a sample
  - Invaluable to map contamination boundaries of materials
Attenuated Total Reflectance (ATR) set-up

- Most versatile instrumentation for fab
- Micro diamond ATR objective to handle micro-areas
  - The red area indicates the IR beam path
  - Penetration depth:

\[
d_p = \frac{\lambda_c}{2\pi \sin^2 \theta - (\eta_s/\eta_c)^2}^{1/2}
\]

where \( \lambda \) is the wavelength of light, \( \lambda_c = \lambda/n_c \) and \( n_s \) is the refractive index of the sample
\( n_c \) is the refractive index of the internal reflection element
\( \theta \) is the internal reflection element
\( \gamma \) is the half-angle acceptance of the microscope objective.
IR Microscope Reflectance Objective

- Modified Schwarzschild all reflective elements objective
- A refractive optical element is mounted in the center to allow inspection of a large field in the visible
Removing atmospheric background absorption

- Absorption from the atmosphere (H2O, CO2 etc.) must be removed from the raw spectrum data
Wavenumber vs Wavelength

- Why use wavenumbers? direct relationship to energy
  - The energy of light can be expressed as:
    \[ E = \frac{hc}{\lambda} = hn \]
    - where \( h \) is Plank’s constant (6.63 \times 10^{-34} \text{ J} \cdot \text{s})
    - \( c \) is the speed of light in vacuum (3.0 \times 10^8 \text{ m/s})
    - \( \lambda \) is the wavelength of the light.

- In practice the IR radiant energy units are wavenumbers \( n \)

- Wavenumbers are the reciprocal of the wavelength, \( \lambda \)
  - i.e. the number of waves per unit length

- The SI unit is \( \text{m}^{-1} \), but a commonly used unit is \( \text{cm}^{-1} \).
  - Reference:

- Conversion between wavelength and wavenumber
  \[ \nu = \frac{1}{\lambda} \times 10^4 \]
  - \( \nu \) in \( \text{cm}^{-1} \), \( \lambda \) in \( \mu\text{m} \)

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Lambert-Beer’s law

- FTIR spectra can provide quantitative information
- Lambert-Beer’s law correlates physical properties and chemical composition:
  - The concentration of a sample can be estimated by:
    - \[ A = -\log T \varepsilon c d \]
  - Where:
    - \( T \) is the intensity of the light transmitted through the sample
    - \( \varepsilon \) is the molar absorption coefficient
    - \( c \) is the sample concentration
    - \( d \) is the sample thickness
Practical FTIR applications in packaging

- Polymer processing
  - Curing
  - Photolitho, metallization etc.

- Plasma etching
  - Descuming, patterning

- Identification of materials:
  - Polymer dielectrics
  - Inorganic thin films
  - Contamination
  - Unknown compounds

- Analysis of formulations
An example of polyimide spectrum
Peaks deconvolution

- Uncovering hidden peaks
- Unmasking peak height
Drying and Curing polymers

- Drying of photo-sensitive materials is critical
  - Impacts photo response

- Optimizing curing:
  - Determine optimum intermediate curing in multi-layer applications
    - Curing level kept low for layer to promote inter-layer bonding
    - Curing level high enough to withstand sputtering thermal load
  - Trade-off curing time vs temperature
  - Checking on consistency of curing level
  - Determining curing level and completion
  - Checking on the effects of novel curing methods
    - Microwave
    - e-beam

- Optimizing curing profile
  - Ramping speed, dwell time
  - Monitoring effects of background curing atmosphere
Evaluation of B-staging a polymer

- Photo polymers are very sensitive to drying conditions.
Distinguishing dried and cured wafers

- Stray wafer lot orphaned after exposure and development
  - No partial curing

![Absorbance vs. Wavenumbers graph](image)
Drying photoresist

- Optimization of positive photoresist drying
Drying polyimide

- Identification of material condensing on walls of a poorly ventilated drying oven

![Spectrogram of solvent condensation on walls of a drying oven.](image)
Monitoring product after curing

- Curing atmosphere:
  - Evaluation of thermo-oxidative and thermal stability
  - Stability check of cured polymers to environment
    - Post curing oxidation in air
  - Troubleshooting curing oven problems
- Moisture absorption
- Evaluation of oxygen or moisture barrier capabilities
- Detection of molecular impurities or additives present in amounts of 1% and in some cases as low as 0.01%
Final cure temperature

- Optimizing and monitoring final curing

![Graph showing final cure temperatures and absorption peaks at 320 °C, 350 °C, and 380 °C.]
Monitoring effects of curing level

- A common bumping job-shop issue:
  - wafers from different sources may react differently
Plasma etching

- Detection of etching endpoint
  - contact via holes
  - polymer
  - oxide

- Detection of etching problems
  - Residual Fluorine on polymer surface
  - Polymer or metal oxidation
  - Polymer degradation: Identification of bonds damaged by plasma chemistry

- Cleaning of via holes
  - Very thin films are not detectable in an optical microscope
  - Over-etching and under-etching control
  - Detection and identification of residues (e.g. ash)
Plasma etching

- Effect of introducing H₂ in etching gas
Plasma etching process development

- Spectra before and after plasma etching

![Spectra comparison graph](image)
Monitoring effects of processing steps

- **Sputtering**
  - Many systems have poor thermal control (no wafer cooling)
  - Monitor effects of thermal load on polymer
  - Cassette to cassette consistency
  - Variation of thermal load imposed within cassette

- **Etching (Wet and Plasma)**
  - Identification of damage caused by etching chemistry
  - Optimize plasma etching gas

- **Photoresist removal**
  - Wet
    - Damage to underlying polymer
    - Check in conjunction with curing level
  - Plasma
    - Optimizing gas mixture and timing
    - Check on descuming

- **Cleaning materials**
  - Damage caused by strong solvents used to remove solder flux
Identification of contamination

■ Flux residues:
  – Present on solder balls
  – Contamination of the passivation layer

■ Chemical contamination of parts in processing
  – e.g. Permeation or absorption of chemicals in a polymer

■ Contamination of parts induced by handling, processing, shipping etc.

■ Aging of vacuum roughing lubricants
  – Deterioration of plasma pump oil
    • Acidification, oxidation or fluorination

■ Vacuum chamber contamination
Identifying contamination

- Degassing from improperly dried photoresist contaminating a stepper optical system
Identification of Materials and Chemicals

- Identification of compounds
  - Matching spectrum of unknown compound with reference spectrum (fingerprinting)
- Identification of functional groups in unknown substances
- Identification of reaction components and kinetic studies of reactions
- Identification of molecular orientation in polymer films
  - Need polarized IR set-up
- Identification of polymers, plastics, and resins
- Analysis of formulations
  - Wet etchants
  - Cleaning solutions
  - Solvents
Monitoring SOG (Spin-on glass)

- Same SOG material on different wafers
Plasma treatment of $\text{Si}_3\text{N}_4$

- Oxidation of the surface after O2 plasma
Monitoring of oxidation of an Aluminum film

From L. Brandner “Ozone Oxidation of Ti and Al on a Flexible Substrate for Thin Film Transistors “ U. Illinois, July 31, 2003
FTIR limitations

- Molecule must be active in the IR region. (When exposed to IR radiation, a minimum of one vibrational motion must alter the net dipole moment of the molecule in order for absorption to be observed.)
- Minimal elemental information is given for most samples.
- Material under test must have some transparency in the spectral region of interest.
- Accuracy greater than 1% obtainable when analysis is done under favorable conditions
- Expect accuracy of ± 5% for routine analyses
Conclusion

- FTIR is a simple and sensitive analytical tool
  - Provide fast data acquisition tool
  - Simple to operate
  - Most useful analytical tool
    - to determine the composition of organic materials
    - to identify IR transparent or semi-transparent inorganic films
    - provides quantitative determination of compounds in mixtures

- Con:
  - Interpretation of the data requires some experience
  - No useful detailed database available for the semiconductor processes