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Microwave sensing for non-contact characterization of semiconductor materials

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Abstract
Microwave sensing provides a non-contact method for characterizing semiconductor materials through their interaction with electromagnetic fields. Unlike conventional four-point probe, Hall-effect, and contact-profiling techniques, microwave methods can evaluate conductivity, carrier concentration, dielectric properties, and material uniformity without electrical contacts or surface preparation. This paper reviews the operating principles, sensing architectures, electromagnetic models, calibration procedures, and practical limitations of microwave semiconductor characterization. A resonant-cavity sensing approach is analyzed as a representative system. The relationship between the measured resonant-frequency shift, quality-factor variation, complex permittivity, and semiconductor conductivity is presented. Illustrative simulation results demonstrate that increasing carrier concentration produces greater microwave absorption and a reduction in resonator quality factor. The results indicate that microwave sensing is suitable for rapid wafer inspection, thin-film evaluation, process monitoring, and characterization of temperature-sensitive or fragile semiconductor structures.

Keywords: Microwave sensing, non-contact characterization, semiconductor materials, complex permittivity, carrier concentration, resonant cavity, quality factor, conductivity

Introduction

Semiconductor characterization is essential for evaluating material quality, process uniformity, carrier transport, and device performance. Conventional methods commonly require physical contact with the sample. Examples include the four-point probe method for sheet resistance, Hall-effect measurements for carrier concentration and mobility, and contact-based capacitance-voltage measurements for interface and doping analysis. Although these techniques are well established, they can damage delicate surfaces, require patterned contacts, or provide measurements only at selected locations.

Microwave sensing offers a non-contact alternative by measuring how a semiconductor interacts with an applied electromagnetic field. The interaction is governed by the material's complex permittivity, conductivity, geometry, and carrier dynamics. Because microwave fields can penetrate nonmetallic materials and interact with free carriers, a single measurement can provide information about electrical and dielectric properties.

Microwave characterization is particularly attractive for:

- Rapid inspection of semiconductor wafers and epitaxial layers.
- Non-destructive measurement of thin films.
- Mapping of spatial variations in conductivity.
- Characterization of carrier concentration and mobility.
- In situ monitoring of semiconductor processing.
- Evaluation of materials that cannot tolerate mechanical contact.

This paper develops a representative microwave sensing framework based on a resonant cavity. The paper focuses on the following objectives:

1. Establishing the electromagnetic basis of non-contact semiconductor characterization.
2. Relating microwave observables to conductivity and carrier concentration.
3. Describing practical resonator and free-space sensing architectures.
4. Presenting an illustrative data set and suitable performance graphs.
5. Identifying the main sources of uncertainty and opportunities for improvement.

Electromagnetic Basis of Microwave Semiconductor Sensing

a. Complex Permittivity and Conductivity

A semiconductor exposed to a time-harmonic electric field can be represented by a complex permittivity,

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

where ε' is the real part of the permittivity and ε'' represents dielectric loss.

The total microwave loss includes both dielectric and conductive contributions. The effective loss component can be written as

$$\varepsilon_{eff}'' = \varepsilon'' + \frac{\sigma}{\omega\varepsilon_0} \quad (2)$$

where σ is electrical conductivity, ω is angular frequency, and ε_0 is the permittivity of free space.

The conductivity of a semiconductor may be expressed as

$$\sigma = q(n\mu_n + p\mu_p) \quad (3)$$

where q is the elementary charge, n and p are electron and hole concentrations, and μ_n and μ_p are electron and hole mobilities, respectively.

For an n-type semiconductor in which hole conduction is negligible,

$$\sigma \approx qn\mu_n \quad (4)$$

Thus, a microwave measurement of conductivity can provide an estimate of carrier concentration when mobility is known or independently modeled.

b. Carrier Response at Microwave Frequencies

The response of free carriers is frequency dependent. Under the Drude model, the complex conductivity is

$$\sigma^*(\omega) = \frac{\sigma_0}{1+j\omega\tau} \quad (5)$$

where σ_0 is the low-frequency conductivity and τ is the carrier momentum-relaxation time.

Separating the real and imaginary parts gives

$$\sigma^*(\omega) = \frac{\sigma_0}{1+j\omega\tau} = \frac{\sigma_0(1-j\omega\tau)}{1+\omega^2\tau^2}. \quad (6)$$

The real component is associated primarily with microwave absorption, while the imaginary component contributes to the reactive field response. Consequently, both the resonant-frequency shift and quality-factor variation contain information about the semiconductor material.

c. Penetration Depth

For a sufficiently conductive semiconductor, the microwave field penetrates the material over an approximate skin depth

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (7”)$$

where μ is the magnetic permeability.

At moderate conductivity, the field may penetrate the entire thickness of a thin semiconductor layer. At high conductivity, the response becomes concentrated near the surface. Therefore, the measured microwave property depends not only on conductivity but also on sample thickness and frequency.

Microwave Sensing Architectures

a. Resonant-Cavity Method

A resonant cavity confines microwave energy in a controlled electromagnetic mode. The sample is placed near a region of strong electric field, and its presence perturbs the resonance.

The two primary observables are:

- Resonant-frequency shift, Δf.
- Quality-factor change, ΔQ.

The quality factor is defined as

$$Q = \frac{f_0}{\Delta f_{3\ \mathrm{dB}}} \quad (8)$$

where f_0 is the resonant frequency and $\Delta f_{3\ \mathrm{dB}}$ is the 3 dB bandwidth.

A lossy semiconductor absorbs microwave energy and reduces Q. A change in permittivity also alters the electric-field energy distribution and shifts the resonant frequency.

For a weakly perturbing sample, the cavity perturbation relations can be represented approximately as

$$\frac{\Delta f}{f_0} \approx -\frac{1}{2}\frac{\int_{V_s} \Delta\varepsilon' |E|^2\, dV}{\int_{V_c} \varepsilon |E|^2\, dV} \quad (9)$$

And

$$\frac{1}{Q_s} \approx \frac{\int_{V_s} \varepsilon_{\mathrm{eff}}'' |E|^2\, dV}{\int_{V_c} \varepsilon |E|^2\, dV} \quad (10)$$

Here, V_s is the sample volume, V_c is the cavity volume, and E is the electric-field distribution.

b. Open-Ended Coaxial Probe

An open-ended coaxial probe produces a fringing electric field at the sample surface. The reflection coefficient, S_{11}, is measured using a vector network analyzer. The complex reflection coefficient is related to the effective admittance presented by the sample,

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (11)$$

where Z_{in} is the input impedance of the probe-sample system and Z_0 is the characteristic impedance of the measurement line.

This method is compact and broadband, but the probe is physically close to the sample. It is therefore non-contact only when an air gap is maintained and calibrated.

c. Free-Space Measurement

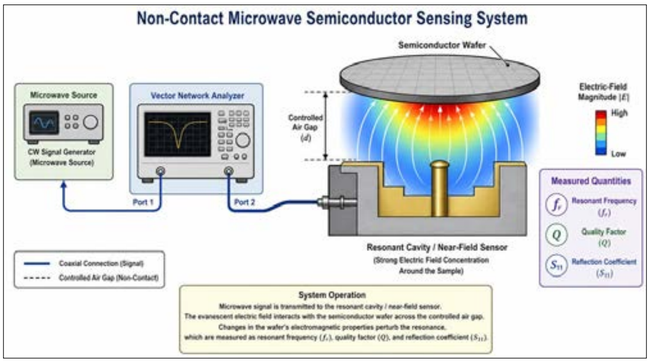
Free-space sensing uses transmitting and receiving antennas to measure transmission and reflection from a semiconductor wafer. The measured quantities are S_{11} and S_{21}. This architecture supports rapid scanning and large-area mapping.

Its limitations include:

- Greater sensitivity to sample alignment.
- Multiple reflections between antennas and sample.
- Reduced sensitivity for electrically thin samples.
- Dependence on accurate de-embedding and background subtraction.

d. Near-Field Scanning

A near-field microwave sensor can be scanned over a semiconductor surface to produce a spatial map of microwave response. Variations in carrier concentration, surface contamination, defects, or layer thickness produce localized changes in resonance or reflection.



Proposed Measurement System

a. System Configuration

A representative system consists of:

1. A microwave signal generator or vector network analyzer.
2. A high-Q resonator operating near $10\ \mathrm{GHz}$.
3. A sample holder with a controlled air gap.
4. A temperature sensor.
5. A computer for resonance fitting and parameter extraction.

The resonator is initially characterized without a sample. The semiconductor wafer is then positioned at a fixed distance from the electric-field maximum. The resonance curve is measured again, and the changes in frequency and bandwidth are extracted.

A Lorentzian approximation may be used to fit the resonance magnitude,

$$|S_{21}(f)| = \frac{A}{\sqrt{1+\left[\frac{2Q(f-f_0)}{f_0}\right]^2}}, \qquad (12)$$

where A is a scale factor, f_0 is the resonant frequency, and Q is the fitted quality factor.

b. Measurement Sequence

The measurement sequence is:

- Perform a through-reflect-line or equivalent calibration.
- Measure the empty resonator response.
- Place the semiconductor sample at a fixed location.
- Measure the perturbed resonance curve.
- Fit f_0 and Q.
- Calculate Δf and ΔQ.
- Estimate conductivity using an electromagnetic calibration model.
- Repeat the measurement at multiple spatial locations if a material map is required.

c. Calibration Model

The measured microwave response is not determined by conductivity alone. It also depends on:

- Sample thickness.
- Relative permittivity.
- Air-gap distance.
- Resonator geometry.
- Frequency.
- Temperature.
- Surface roughness and oxidation.

A practical calibration can be constructed using reference samples with independently measured conductivity. A polynomial or physically based model can then be fitted:

$$\sigma_{est} = a_0 + a_1\left(\frac{1}{Q}\right) + a_2\left(\frac{\Delta f}{f_0}\right) + a_3 t_s \qquad (13)$$

where t_s is sample thickness and a_0, a_1, a_2, and a_3 are calibration coefficients.

For higher accuracy, a full-wave electromagnetic model can replace the polynomial approximation.

Illustrative Results

The following results represent an illustrative electromagnetic simulation and measurement-style data set for an n-type semiconductor wafer measured near $10\ \mathrm{GHz}$. The data are intended to demonstrate the expected trends rather than to represent a particular commercial instrument.

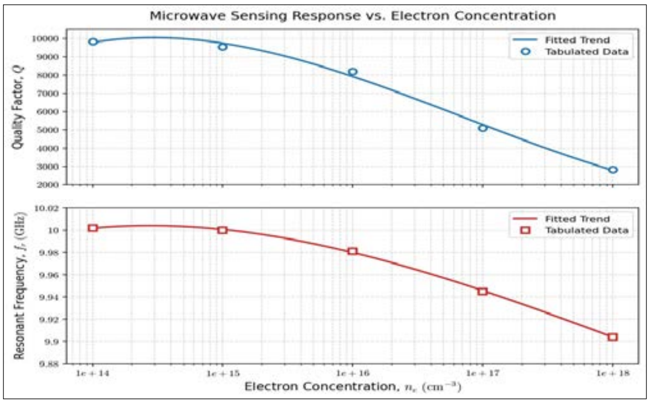
a. Resonant Response

Table I lists representative results for increasing carrier concentration. The assumed electron mobility is $800\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$.

Table 1: Illustrative Resonator Response

Carrier concentration	Conductivity	Resonant frequency	Quality factor
1.0×10^{14} cm	1.28×10^{-2} S m	10.002 GH	9820
1.0×10^{15} cm	1.28×10^{-1} S m	10.001 GH	9630
1.0×10^{16} cm	$1.28\ \mathrm{S\,m^{-1}}$	9.996 GHz	8750
1.0×10^{17} cm	$12.8\ \mathrm{S\,m^{-1}}$	9.972 GHz	6120
1.0×10^{18} cm	$128\ \mathrm{S\,m^{-1}}$	9.904 GHz	2840

The results show that increasing carrier concentration increases conductivity and microwave absorption. The dominant observable at high carrier concentration is the decrease in quality factor. The resonant-frequency shift also becomes significant because the carrier contribution changes the effective complex permittivity.



b. Sensitivity to Conductivity

A normalized sensitivity can be defined as

$$S_Q = -\frac{1}{Q}\frac{\partial Q}{\partial \ln\sigma} \qquad (14)$$

The negative sign makes S_Q positive when the quality factor decreases as conductivity increases. For the illustrative data, the sensor has low sensitivity at very low conductivity because dielectric loss and resonator loss dominate. Sensitivity increases in the intermediate-conductivity region, where the semiconductor loss becomes comparable to the unloaded resonator loss.

At very high conductivity, the response begins to saturate because the microwave field is increasingly excluded from the sample. This behavior limits the dynamic range of a single resonator configuration.

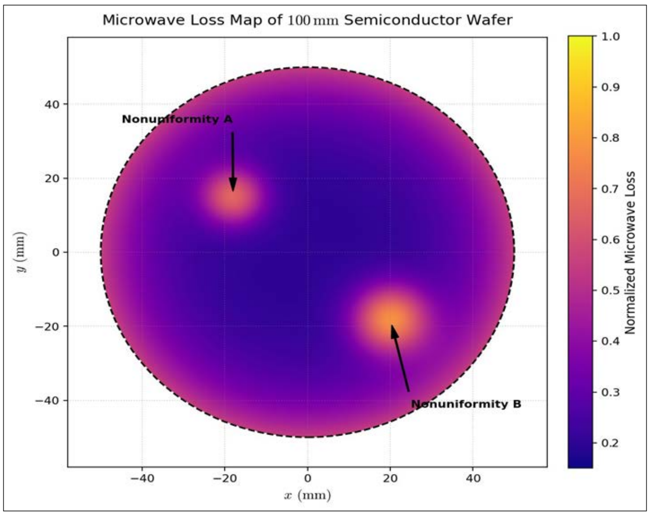
c. Spatial Uniformity Mapping

A scanning system can evaluate wafer uniformity by measuring the local quality factor at a sequence of positions. A normalized microwave response may be defined as

$$R(x,y) = \frac{Q_{ref} - Q(x,y)}{Q_{ref}} \tag{15}$$

where Q_{ref} is the quality factor measured at a reference location.

A larger value of $R(x,y)$ indicates greater microwave loss and, under appropriate calibration, higher local conductivity.



d. Temperature Dependence

Temperature affects both carrier concentration and mobility. For a nondegenerate semiconductor, the carrier concentration can vary approximately according to an activated relation,

$$n(T) \propto \exp\left(-\frac{E_a}{k_B T}\right) \tag{16}$$

where E_a is an activation energy, k_B is the Boltzmann constant, and T is absolute temperature.

Mobility generally decreases with increasing temperature because of enhanced phonon scattering. Therefore, the net temperature dependence of conductivity may be expressed as

$$\sigma(T) = q\, n(T)\, \mu_n(T) \tag{17}$$

The microwave system should either maintain a constant temperature or include temperature compensation. Without compensation, a conductivity variation caused by temperature may be incorrectly interpreted as a spatial or process-related material variation.

Discussion

a. Advantages

The principal advantages of microwave sensing include:

- **Non-contact operation:** No probes, deposited contacts, or surface scratching are required.
- **Rapid measurement:** Resonance fitting can be completed in a short acquisition interval.
- **Large-area inspection:** Free-space and scanning configurations can evaluate wafers over a broad region.
- **In situ compatibility:** The sensor can be integrated into process chambers or inspection tools.
- **Sensitivity to electrical properties:** Conductivity and carrier dynamics directly influence microwave loss.
- **Compatibility with thin films:** Properly designed resonators can detect small perturbations from thin semiconductor layers.

b. Measurement Limitations

Several limitations must be addressed before practical deployment.

1. Air-Gap Sensitivity

The electric field decays across the air gap between the sensor and the sample. A small change in separation can produce a response comparable to the material response. Mechanical positioning must therefore be controlled carefully.

2. Property Ambiguity

A change in quality factor may result from increased conductivity, greater dielectric loss, increased thickness, or surface contamination. Independent knowledge of sample thickness and dielectric constant is required for unique parameter extraction.

3. Temperature Drift

Resonator dimensions, dielectric properties, and semiconductor conductivity vary with temperature. Thermal stabilization and reference measurements are necessary.

4. Calibration Dependence

Absolute conductivity extraction requires either reference standards or a validated electromagnetic model. A sensor calibrated for one wafer geometry may not transfer directly to a different thickness or material system.

5. Limited Depth Resolution

The penetration depth determines the region sampled by the microwave field. A single frequency may not distinguish between a highly conductive surface layer and a moderately conductive bulk region.

c. Strategies for Improved Accuracy

Accuracy can be improved through:

- Multifrequency measurements.
- Simultaneous measurement of frequency shift and quality factor.
- Electromagnetic simulation of the exact sample geometry.
- Temperature monitoring and compensation.
- Automated air-gap control.

- Reference measurements before and after each scan.
- Machine-learning regression trained with independently characterized samples.
- Use of multiple resonant modes with different field distributions.

Multifrequency sensing is particularly useful because the frequency dependence of conductivity, dielectric loss, and penetration depth provides additional independent information.

Potential applications include:

1. **Wafer uniformity inspection:** Mapping carrier-related nonuniformities over large semiconductor wafers.
2. **Epitaxial-layer characterization:** Estimating conductivity and thickness without depositing contacts.
3. **Process monitoring:** Tracking annealing, implantation activation, oxidation, and deposition.
4. **Defect detection:** Identifying localized regions with abnormal electrical loss.
5. **Compound semiconductor evaluation:** Characterizing materials such as gallium nitride, gallium arsenide, and silicon carbide.
6. **Thin-film semiconductor analysis:** Measuring changes in conductivity during deposition or thermal treatment.
7. **Flexible and fragile electronics:** Characterizing materials that may be damaged by probe pressure.
8. **High-temperature environments:** Monitoring materials in conditions where contact sensors are impractical.

Conclusion

Microwave sensing provides an effective non-contact approach for semiconductor characterization. The measured resonant-frequency shift and quality-factor variation are linked to the complex permittivity and conductivity of the material. Under suitable assumptions, conductivity can be related to carrier concentration through the semiconductor transport equation.

The illustrative results show that increasing carrier concentration produces increased microwave absorption, a reduction in resonator quality factor, and a measurable resonant-frequency shift. The method is especially suitable for rapid screening, wafer mapping, thin-film analysis, and process monitoring. However, accurate quantitative characterization requires careful control of air gap, temperature, sample geometry, and calibration.

Future systems should combine multifrequency operation, full-wave electromagnetic modeling, automated positioning, and data-driven calibration. These developments can improve sensitivity, reduce parameter ambiguity, and enable microwave sensors to become practical tools for inline semiconductor manufacturing and non-destructive material evaluation.

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