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THERMAL WAVE IMAGING OF GaAs MATERIAL AND DEVICES*

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Abstract - Thermal wave (TW) imaging was employed to delineate intrinsic properties of gallium arsenide (GaAs) semiconductor material and physical properties of GaAs devices not discernible by conventional techniques of electron, optical, or acoustic microscopy.

I - INTRODUCTION

Thermal wave microscopy, also known as electron acoustic microscopy, is a fairly recent development disclosed in 1980 almost simultaneously by Brandis and Rosencwaig [1] and by Cargill [2]. The technique entails adding a beam blanking driver, an acoustic transducer, and a phase-sensitive amplifier to a standard scanning electron microscope (SEM).** By modulating the primary electron beam at a frequency in the range of 100 kHz to 2 MHz, periodic surface heating of the sample generates a thermal wave. Propagation of the thermal wave is highly sensitive to localized discontinuities in thermal properties such as conductivity, specific heat, and density, which can alter the phase, intensity, and direction of the wave. The critically damped thermal wave decays exponentially in a few microns, generating a thermoacoustic wave that has the same frequency but much longer diffusion length, typically a few millimeters. A piezoelectric transducer affixed to the back of the sample is used to detect the thermoacoustic wave and provide a signal for imaging. The acoustic wave, therefore, merely serves to transport the information imparted on the thermal wave by thermal sensitive features in the near surface region of the sample. The expression for the thermal wavelength, $\lambda_T$, is

$$\lambda_T = 2\pi \left[ \frac{K}{\rho c_{\text{ef}}} \right]^{1/2}$$

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**A Cambridge S250 SEM with an LaB$_6$ electron gun and a Therma-Wave, Inc., Model 102 Thermal Wave Analyzer with PZT transducer, preamp, and electrostatic beam blanking were used. Operating conditions were $E_0 = 30$ kV, $I_0 = 1$ $\mu$A (unblanked beam), and 50-µm final aperture. Samples were uncoated.
where

\( K \) = thermal conductivity
\( \rho \) = density
\( C \) = specific heat
\( f \) = frequency of the pulsed electron beam

Typically, it is local variations in the thermal conductivity, \( K \), that have the greatest effect on the intensity and phase of the thermal wave. Detailed descriptions of TW microscopy have been published \([3],[4]\), as have applications to metals and silicon semiconductors \([5],[6]\), although no results have heretofore been published on GaAs devices.

II - ANALYSIS OF GALLIUM ARSENIDE

Gallium arsenide, widely used in microwave device fabrication, is an excellent subject for TW analysis. With a relatively low thermal conductivity (1/3 that of silicon), GaAs exhibits superior spatial and depth resolution in the TW mode. Figure 1 shows the secondary electron (SE) image and three TW images of a portion of a 4-GHz GaAs field-effect transistor (FET) that consist of areas of alloyed Au-Ge-Ni ohmic contacts which form the source and drain bounding a narrow Schottky gate line. The three images were taken at different frequency and phase conditions to delineate thermal features at different depths in the ohmic contact: lb near the outer surface, lc near the mid-point of the metal layer, and ld at the contact/GaAs interface which lies \( \approx 4 \) kÅ beneath the surface. The randomly oriented dark features seen in TW images lb and lc are Ge- and Ni-rich grains which segregated during the alloying process. The most interesting feature is the dark rectangular area evident in ld. This area is the only remaining active region of n-type epitaxial GaAs. The neighboring area has been isolated by bombardment with 40-kV \( \mathrm{H}^+ \) ions at \( 10^{13} \) ions/cm\(^2\), which causes an increased density of defects and reduction of thermal conductivity. Since the propagation of thermal waves is a transport phenomenon, it is highly sensitive to scattering by phonon defects. The defect concentration in the proton bombarded region is \( 2 \times 10^{19} \) ions/cm\(^3\) in the top 1/2-um layer of GaAs.

Thermal wave analysis of another FET design, a co-planar microwave guide, is shown in Figure 2. This device, with dual 2-um gates, was fabricated by implanting semi-insulating GaAs with \( ^{79}\mathrm{Se}^+ \) ions at a concentration of \( 1.4 \times 10^{17} \) ions/cm\(^3\) and then bombarding intermediate areas with protons to isolate the Se-activated regions. The Au-Ge-Ni ohmic contacts and the Cr-Au gate contact were then applied. For the TW analysis, phase detection parameters were optimized to separately show the gate contacts (Figure 2b) and the underlying Se implant (Figure 2c). The defects in the active region (dark bands) of the TW image are probably a result of discontinuities in the photoresist, which failed to mask the protons during the isolation implant step. Defects of this nature will adversely affect the performance of the FET.
On each GaAs wafer that is processed, it is standard practice to include various test patterns that are used to evaluate the quality of the semiconductor and the fabrication process. One such pattern is the gated Van der Pauw, Figure 3, which is used to determine the carrier mobility profile based on Hall effect measurements with back bias on a Schottky contact. Delineation by TW microscopy of the silicon-implanted region, Au-Ge-Ni ohmic contact, and Cr-Au Schottky gate contacts is depicted in the figure. The defect evident in the active region, near the lower righthand contact, was not discernible with optical or SE analysis. It is attributed to a lattice defect in the semiconductor material.

The resolution test patterns, Figure 4, serve as a tool for linewidth evaluation of various processing steps, which are practiced in the following order on semi-insulating GaAs: Area 4—28Si+ activation implant (3 x 10^17 atoms/cm^3 to ~3 kÅ depth); Area 6—alloyed ohmic contact of Au-Ge-Ni (1,600 Å total); Areas 1, 2, and 3—Cr-Au (100/4,000 Å) gate mask levels; and Area 5—no processing. The interesting features in the TW image of this pattern are the detection of the Si-implanted region in area 4 and the high definition of the gate pattern in area 1. The implanted lines in area 4 are nominally 3 μm wide with 3-μm spaces. Area 1 consists of patterned lines of Cr-Au 0.7 μm wide with 2-μm center-to-center spacing.
For a flat surface and homogeneous material, the theoretical resolution obtainable in TW imaging is limited by the thermal diffusion length, $\lambda_t/2\pi$ [7], provided that the probe diameter is sufficiently small. The intensity of the thermal wave decays to $1/e$ in the distance of one thermal diffusion length. For GaAs, based on values for $K$, $\rho$, and $C$ from Sze [8], the theoretical resolution at $f = 1$ MHz is 2.8 $\mu$m. However, in the practical sense, spatial point-to-point resolution in TW microscopy can often exceed the theoretical limit when samples are not flat and homogeneous. This is the case for metal contacts on GaAs. Line edge resolution of $<2$ kÅ in TW images of 1-μm-wide lines of Cr-Au on GaAs was measured. Also, features shallower than 2 kÅ were imaged with high contrast.

IV - CONCLUSION

Thermal wave microscopy is a useful tool for research, process control, and failure analysis of GaAs microelectronic devices. It is unique in its ability to selectively image depth levels of features such as ion implants, crystal defects, and metal/semiconductor contact interfaces with resolution $<2$ kÅ. With further effort in the areas of digital image analysis and theoretical interpretation, it should be possible to quantitatively interpret thermal wave images for subsurface features, such as carrier concentration profiles and the density of flaws in semiconductor materials and devices.

V - REFERENCES