SPIE Newsroom

10.1117/2.1200806.1157

Looking at the nanomechanics of electronic devices under the scanning electron microscope

Giuseppe Pezzotti, Andrea Leto, Alessandro Alan Porporati, Marco Deluca, Atsuo Matsutani, Maria Chiara Munisso, and Wenliang Zhu

A combination of advanced spectroscopy and cathodoluminescence aids in quantifying the stress states in sub-micron-sized electronic heterostructures.

Modern industry routinely uses sophisticated microscopic methods for quality control and for predicting the performance of manufactured products. These processes typically exploit optical emission and scattering phenomena—such as electron backscattered diffraction and energy-dispersive x-ray spectroscopy—using equipment attached to conventional scanning electron microscopy (SEM). In silicon-based metal oxide semiconductor (MOS) devices, residual stresses may remain from the manufacturing process owing to a mismatch in thermal expansion coefficients between constituent materials. Thermal fatigue and electromigration (displacement of atoms induced by electric current) phenomena can also affect the devices' micromechanical state. Up to now, SEM has not been applied to these problems for two reasons. First, the effects of strain on electronic transitions arising from band-gap or optically active point defects, as well as their interaction with the electron probe, were not fully understood. Second, no comprehensive algorithm could be found that took into account the superposition of several chemical, physical, and mechanical effects (i.e., temperature gradients, self-absorption, chemical gradients) to extract the stress information from the luminescence spectrum. Yet, the spatial resolution of the SEM would be highly advantageous in residual stress assessment.

We recently developed a spectroscopic method for analyzing materials and devices in the SEM that works by visualizing surface and subsurface stress fields. Further, we have used the technique to solve a number of important industrial problems, for example, the stress stored in interconnect structures (like interlayer dielectrics) and in III-V semiconductor-based electronic devices.[1–3] The method is based on piezospectroscopic (PS) analysis of the cathodoluminescence (CL) emission, which examines the alteration of a luminescence spectrum on applied or residual stress or strain. Here we report how PS analysis can be a valuable addition to chemical and crystallographic studies of electronic materials and devices in SEM by providing useful micro- and

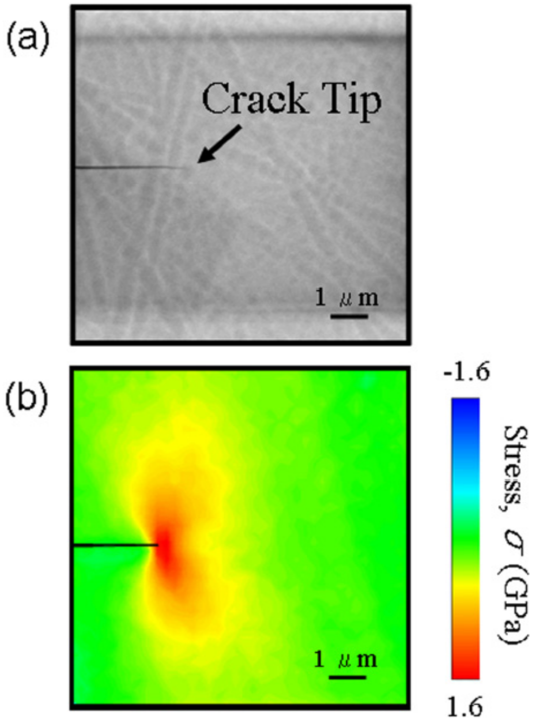

Figure 1. An SEM image (a) and a CL/PS stress image (b) of the immediate neighborhood of the crack tip in a gallium nitride crystal. The stress map represents the spatial variation of the trace of the stress tensor acquired with a spatial resolution of 30nm.

Continued on next page

nanomechanical information. Coupled with CL and using CL deconvolution algorithms, the SEM can help to quantify stress states in sub-micron-sized electronic heterostructures.

CL spectroscopic outputs present a high intrinsic correlation. Complex deconvolution methods need to be applied to extract the spectroscopic output from overlapping effects. The data treatment techniques we used include case-by-case development of new algorithms for various luminescence bands in a variety of materials. In addition, owing to electron scattering, the data collection area is larger and deeper than the size of the surface pixel adopted in scanning with the electron beam, and most pixels will contain a weighted mixture of stress information. For this reason, the recorded spectrum must also be spatially deconvoluted to account for the effect of the electron probe. Highly graded stress field analysis requires maximized light efficiency in the SEM and new algorithms for the spatial deconvolution of electrostimulated luminescent probes.[1–3]

There are three different families of luminescence stress sensors: band-gap emission from semiconductors (e.g., gallium nitride and gallium arsenide), luminescence from substitutional impurities and vacancies (e.g., trivalent chromium or fluoride centers in sapphire), and emission bands from oxygen-related point defects in glassy dielectrics (e.g., nonbridging oxygen hole centers in amorphous silica). In the PS analysis, the observed spectral shift obeys different rules depending on the physical nature of the spectroscopic sensor available for the stress measurement. The PS behavior of bands arising from point defects obeys Grabner's formalism, according to which the wavelength shift is linearly related to the trace of the stress tensor. On the other hand, in the case of band-gap emission, the observed spectral stress dependence follows the strain Hamiltonian of the material investigated.

One of the steepest stress gradients is located at the tip of a crack propagating in a brittle solid as shown in Figure 1(a) and (b). For silicon-based MOS devices, our results show that a quantitative assessment can be made of residual stresses in the silica side of these devices by using the CL/PS effect. The stress assessment is complementary to a PS Raman evaluation on the silicon side of the device (see Figure 2).

In conclusion, we have shown that quantitative experimental assessments of stress with nanometer spatial resolution can be obtained with SEM for semiconductor materials and devices. Spatially resolved PS procedures, when correctly interpreted, enable access to stress and strain information, regardless of whether the observed spectrum arises from band gap or optically active point defects. In the near future, this information could be condensed into a metrological multifunctional tool optimized for measurement of real-time physical, chemical, and mechanical material parameters on the scale of a single nanometer in the next generation of electronic devices.

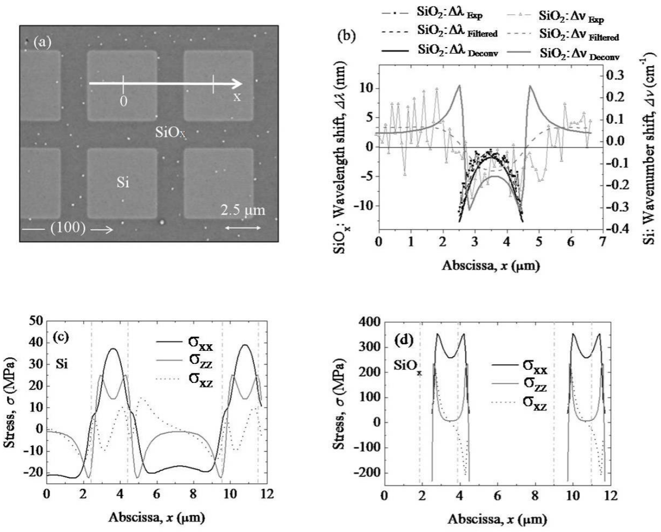

Figure 2. (a) An SEM image of the measurement location. (b) The spectral shift results of line scans (performed across a silica trench in MOS by the CL/PS method and in the silicon areas by the Raman PS method). (c and d) The respective deconvoluted stress components. Si: Silicon. SiO_x: Silicon oxide.

Author Information

Giuseppe Pezzotti, Andrea Leto, Marco Deluca,
Maria Chiara Munisso, and Wenliang Zhu
Ceramic Physics Laboratory
& Research Institute for Nanoscience
Kyoto Institute of Technology
Kyoto, Japan

Giuseppe Pezzotti graduated from Rome University, La Sapienza, and received his PhD from Osaka University. Since 2000, he has been a full professor at Kyoto Institute of Technology. He also directs the Research Institute for Nanoscience, in Kyoto, and is an adjunct professor for the Orthopaedic Faculty of Loma Linda University, CA.

Alessandro Alan Porporati
Piezotech Japan, Ltd.
Kyoto, Japan

Continued on next page

Atsuo Matsutani
Ceramic Physics Laboratory
& Research Institute for Nanoscience
Kyoto Institute of Technology
Kyoto, Japan

Piezotech Japan, Ltd.
Kyoto, Japan

References

1. A. A. Porporati, N. Furukawa, W. Zhu, and G. Pezzotti, *Deformation potentials of Si-doped GaAs from microscopic residual stress fields*, **J. Appl. Phys 102**, p. 083102, 2007. doi:10.1063/1.2798603
2. A. Leto, A. A. Porporati, W. Zhu, M. Green, and G. Pezzotti, *High-resolution stress assessments of interconnect/dielectric electronic patterns using optically active point-defects of silica glass as stress sensor*, **J. Appl. Phys 101**, p. 093514, 2007. doi:10.1063/1.2723193
3. W. Zhu, A. A. Porporati, A. Matsutani, N. Lama, and G. Pezzotti, *Spatially resolved crack-tip stress analysis in semiconductor by cathodoluminescence piezospectroscopy*, **J. Appl. Phys 101**, p. 103531, 2007. doi:10.1063/1.2735681