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Two-dimensional transverse cross-section nanopotentiometry of actively driven buried-heterostructure multiple-quantum-well lasers

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We report results of two-dimensional local potential measurement of the transverse cross-section of operating buried-heterostructure (BH) multiple-quantum-well lasers. The measured two-dimensional image of potential distribution resolved clearly the multi-quantum-well active region and the p - n - p - n current-blocking structure of the BH laser, showing close correlation to the scanning spreading resistance microscopy image. Nanopotentiometry measurements were also performed on the p - n - p - n current-blocking structure of a BH laser under different forward bias voltages. The nanopotentiometry results provide direct insight into the behavior of p - n - p - n current-blocking layers intended to minimize current leakage. Our results demonstrate the application of nanopotentiometry to the delineation of complex buried structures in quantum optoelectronic devices. © 2002 American Vacuum Society. [DOI: 10.1116/1.1524150]

I. INTRODUCTION

In the past decade, a number of methods have been developed to map dopant concentration on the nanometer scale in two and three dimensions.^{1,2} Atomic force microscopy (AFM) based techniques such as scanning spreading resistance microscopy (SSRM)^{3–5} and scanning capacitance microscopy (SCM)^{6–8} have been used for two-dimensional (2D) dopant profiling in semiconductor devices. The quantitative capabilities of these techniques have been demonstrated on unbiased Si-based structures^{9–11} and InP-based structures.^{12–14} More recently, Zavvalov and his co-workers¹⁵ reported the application of SCM on an actively biased cross-sectioned metal–oxide–semiconductor field-effect transistor (MOSFET). Through the use of a physical model, the acquired SCM data were converted to a 2D dopant profile.

If the internal operation of semiconductor devices is to be probed directly, then the challenge is twofold: to resolve as directly as possible the internal potential and carrier density distribution; and to do so in an operating device without substantially perturbing its behavior in the course of the measurement process. To probe only the input/output characteristics at the device terminals is to lose direct information about details of internal dynamics; and to probe the internal nanostructure at zero device bias alone, or with passage of substantial current through the probe, does not allow us to observe the device in its intended state of operation.

Nanopotentiometry,^{16,17} which we also call scanning voltage microscopy, is a tool based on AFM, which is capable of measuring directly and with high spatial resolution the voltage distribution on a cross section through a fully operating

semiconductor device. It is worth noting that the measured voltage at each point inside a given semiconductor structure is a macroscopic quantity, while the internal potential profile of the structure, or more specifically, the potential used in a single-particle Schrödinger equation, is a microscopic quantity. As discussed in Sec. III, the macroscopic quantity of voltage can be related to the microscopic quantity of potential in a semiclassical regime. The determination of internal potential distribution is pertinent to many other local properties, such as carrier concentration, band positions, quasi-Fermi level position, etc. Nanopotentiometry sheds light directly on the electrical characteristics of the devices under a variety of operating conditions. In this sense, nanopotentiometry provides a close view into the behavior of operating semiconductor devices.

Trenkler and co-workers¹⁶ demonstrated the successful application of nanopotentiometry on Si-based MOSFET devices. Nanopotentiometry enables 2D transverse profiling—inaccessible in conventional one-dimensional destructive techniques such as secondary ion mass spectroscopy. Nanopotentiometry measurements on fully operational optoelectronic devices have not been reported.

Several other scanning probe microscope based techniques have been proposed as possible candidates for mapping the cross-sectional local potential of a semiconductor device. These include electric force microscopy (EFM) and scanning Kelvin probe force microscopy (SKPM). EFM^{18,19} is a phase contrast imaging technique with a complicated quantification procedure—the variations in the electric field gradient above a sample are measured in the actual process. As a consequence, EFM is not suitable for a direct quantitative potential measurement. In SKPM,^{20,21} the tip is scanned in noncontact mode across the cross-section surface of the device. A direct current (dc) bias is applied to the conductive tip to match the local potential of the surface by minimizing

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FIG. 1. Schematic diagram of nanopotentiometry experimental setup. A dc current source was used above ~ 1 mA current. In measurement performed below ~ 1 mA a reference resistance of 99.9Ω was connected in series with the laser device as a current limiter and a dc voltage source was used.

the electric force acting between the tip and the sample surface. However, The technique provides limited spatial resolution (50–100 nm) and is constrained by its susceptibility to static surface charges.

In nanopotentiometry, a conductive AFM tip is used to measure the voltage distribution on a surface. The conductive probe is scanned in contact mode over the cross section of the device. The local voltage is measured by a precise voltage meter with ultrahigh input impedance. The obtainable spatial resolution is on the same order of the radius of the AFM tip (~ 20 nm). The technique has advantages over other diagnostic methods in that: (1) it is essentially nondestructive; (2) it does not significantly perturb the device under test; (3) it enables characterization of operating, even lasing, devices; and (4) it resolves the 2D transverse cross section of devices, which is particularly important in buried heterostructure (BH) laser devices.

We report in the present article the extension of the nanopotentiometry technique to a BH multi-quantum-well (MQW) laser under forward operating bias. By virtue of their tight confinement of carriers and photons to an active region defined by a semiconductor current-blocking structure, BH lasers exhibit low threshold current, low thermal chirping and a stable, circular transverse far-field profile, and thus are intended for directly-modulated deployment. SSRM was first performed to delineate the buried transverse cross-section structure of the laser. A number of high-resolution 2D voltage maps were measured across the MQW active region and the p - n - p - n current-blocking structure of the laser. Individual quantum wells were resolved with nanopotentiometry. Quantitative analysis on the measured nanopotentiometry data of the laser biased at different voltages are presented and discussion is given as well. The results give insight into a key problem in advanced semiconductor laser engineering: revealing the mechanism and influence of current leakage over the current-blocking structure and/or over and around the active region.²²

II. EXPERIMENT

Figure 1 shows the schematic experimental setup of the nanopotentiometry measurement. A BH MQW laser (uncoated, fresh-cleaved facet facing up) was mounted in a commercially available atomic force microscope [Digital Instruments (DI), Dimension 3100]. A conductive AFM probe was

scanned in contact mode over the cross section of the device for nanopotentiometry measurements. The laser was set under operation by applying variable forward bias voltages externally. The voltage signal from the conductive probe was measured by a voltage meter with high input impedance (Keithley 6517 A) and acquired by the AFM computer (DI, Nanoscope IIIa) via a signal access module (DI). The Keithley 6517A is an electrometer, which can measure multiple functions including voltage, current, resistance, and charge. The internal operational amplifier (Op Amp) circuit is reconfigured depending on the function selected. In voltage function, the basic design is a unity gain Op Amp commonly referred to as a voltage follower. Because of this design, it offers a high input impedance, typically $> 2 \times 10^{14} \Omega$, and measures the voltage with minimum perturbation.

The AFM was also equipped with a commercial SSRM application module option which implements a sensitive six decade (1 mA–1 nA) logarithmic amplifier to measure the electric current flowing from the tip through the sample and to the sample chuck as a function of AFM tip position. The SSRM measurements were performed under contact-mode AFM feedback conditions. The tip was scanned in SSRM measurements at 0.25 – $4 \mu\text{m/s}$ with forces in the range of 2 – $5 \mu\text{N}$. The dc bias applied to the AFM tip was in a range of 0.5 – 1.0 V.

In nanopotentiometry mode, the tip scan rate varied from 0.004 to $0.5 \mu\text{m/s}$, depending on the specific requirement of the measurement. The contact force was set high enough to make sure the tip mechanically penetrated the native oxide layer at the sample surface to establish a good electrical contact. The measurements were performed using commercially available boron-doped diamond coated cantilever tips (Digital Instruments, spring constant = 40 N/m), which have been proven to allow quantitative experimental measurements.^{13,23}

The MQW active region of the BH (InGaAsP/InP) lasers was grown by metalorganic chemical vapor deposition. The mesa of the laser was buried beneath a four-InP-layer thyristor structure with alternating doping type. The laser samples were metallized to produce ohmic contacts. A polish-free sample preparation procedure²³ was taken to produce clean bar cleaves devoid of fracture lines and to minimize over edge current leakage. The sample bar was then mounted with the cleaved edge facing up in a metal clamp, with a probe that allowed a single device to be biased. The current–voltage characteristics of the laser devices were measured before, during, and after the nanopotentiometry experiment. No change was observed in device electrical behavior. The topographic AFM image of the device surface, obtained simultaneously with the SSRM and nanopotentiometry data, showed no perceptible features.

III. RESULTS AND DISCUSSION

Scanning spreading resistance microscopy was deployed to examine the cross section of the laser structures prior to the nanopotentiometry measurements. Figure 2 shows a SSRM image obtained on the uncoated facet of the BH MQW laser device. The bias voltage was 0.5 V and the tip

FIG. 2. SSRM image of a BH MQW laser in cross section. The tip bias was 0.5 V and the scan rate was 0.25 Hz. The image area is approximately $5 \times 5 \mu\text{m}$.

scan rate was 0.25 Hz. The n^+ substrate is the bright band at the bottom. The buried mesa structure is clearly resolved in the SSRM image. The narrow, bright strip around the center of the image is the MQW active region, which is clad by p - and n -doped layers above and below. At the left and right sides of the active region are the symmetric p - n - p - n current-blocking structures. Damage induced during engaging of the tip is visible on the left side of the SSRM image. We find that the first SSRM image typically gives the best results. This problem is less marked for nanopotentiometry, where no current flows. Further details about this BH laser, such as dopant levels and a detailed discussion of SSRM and SCM results, can be found in our previous article.¹⁴

Following completion of the SSRM measurements, the experimental setup was changed to allow the nanopotentiometry measurement. Figure 3 shows the 2D voltage profile acquired under a dc forward bias of 0.845 V, which resulted in a current of 10.55 mA (above lasing threshold). The buried mesa is clearly resolved in the nanopotentiometry image and correlates well to the structure shown in Fig. 2. The narrow strip labeled with an arrow is the MQW active region, clad by p - and n -doped layers from the left and right. At the top are the p - n - p - n current-blocking structures. Individual quantum well/barrier periods were resolved by slowing down the nanopotentiometry scan, as shown in the inset. The sharp delineation of the MQW active region reflects the high spatial resolution (sub $\sim 20 \text{ nm}$) attainable with these measurements. The accumulated voltage drop from the p -metal to the substrate measured from the nanopotentiometry is 0.844 V, in good agreement with the external voltage applied to the device. The voltage is nearly uniform over the n -doped regions due to the high electron mobility and doping concentration. Dips over the MQW active region and the second p -doped layer from the left side are perceptible, indicating

FIG. 3. Two-dimensional nanopotentiometry image of a BH laser under forward bias of 0.845 V. The scan rate was 0.005 Hz. The inset shows cross-sectional voltage distribution of a zoom-in nanopotentiometry scan across the MQW active region. Individual well/barrier periods were resolved.

that the voltage in these layers is actually higher than in their neighboring regions.

The dip in the cross-sectional voltage drop curve (as shown in the inset) might imply a local energy minimum in potential for electrons, which is in agreement with the carrier trap nature of the MQW active region. The formation of local energy minimum may be due to the pinning of Fermi levels in quantum wells and the difference of material properties (such as band gap, electron affinity) between InP and InGaAsP quaternary materials. As the laser was biased above threshold, the quasi-Fermi level was pinned and carriers were injected into the active region predominantly through diffusion from left (holes) and right sides (electrons). The holes and electrons were then captured in quantum wells and recombined for light emission. Since the thickness of the MQW active region is much smaller than the typical diffusion length in the quaternary material, considerably high diffusion current is expected to flow through the active region at or above threshold bias. The charge screening effect may have an impact on the nanopotentiometry measurement from a semiclassical standpoint, particularly when the carrier density accumulates high enough as the laser is biased above threshold. Because of the sluggishness of holes, the carrier density is often not uniform across the active region,^{24,25} causing the nonmonotonic variation of the local voltage. Surface effects could play an important role in the nanopotentiometry measurement, as will be discussed shortly.

The electrical and optical performance of the BH MQW laser depends sensitively on the properties of the p - n - p - n thyristor structure. A well-designed and fabricated p - n - p - n current blocking structure will minimize current leakage. The dopant and voltage profiles play a key role in determining the electrical properties of the p - n - p - n thyristor. This information has yet to be measured directly for an actively biased device, although numerical modeling has been used to pro-

FIG. 4. SSRM image of the p - n - p - n current-blocking structure of the BH laser device. The tip bias was 1.0 V and the scan rate was 0.5 Hz.

vide simulation results.²⁴ We focus therefore on the experimental determination of the actual dopant and voltage profiles across the current-blocking region of a BH laser under unbiased or biased conditions.

Figure 4 shows a typical SSRM current image obtained on the transverse cross section of the p - n - p - n current blocking structure in the BH MQW laser devices. The bias voltage was 1.0 V and the tip scan rate was 0.5 Hz. The top surface is at the left hand edge of the image, while the n^+ substrate is the bright band at the right. The SSRM image can be compared with the known nominal doping levels of the p - n - p - n thyristor structure. The first layer from the left side (p doped) has higher doping concentration than that of the third layer (p doped) and is brighter in color (higher current under the same dc bias voltage). Similar color contrast is observed between the second (n -type, lower doping concentration) and the fourth (n -type_substrate, higher doping concentration) layers. The depletion regions of p - n junctions are resolved due to the low conductivity as manifested in the darker lines in the SSRM image. We have previously shown that, using known dopant staircase samples to calibrate the instrumentation, the acquired SSRM data may be converted to dopant concentration with good accuracy.¹⁴

Figure 5 shows a 2D voltage drop profile across the p - n - p - n current blocking layers of the BH laser under forward bias of 0.745 V. The accumulated voltage drop from the p -metal to the substrate measured from the image is 0.741 V. Five strips are clearly resolved from the left to the right in the image, corresponding to p -metal layer and the four layers of the p - n - p - n structure, respectively. The voltage remains constant in each of the two n -doped regions, as seen in Fig. 3. Substantial voltage changes (rise/fall) at the depletion regions of p - n junctions are clearly observed. As expected, the voltage drop occurs predominantly across high impen-

FIG. 5. Two-dimensional nanopotentiometry image of the p - n - p - n structure of a BH laser under forward bias of 0.745 V. Significant voltage changes (rise/fall) at p - n junctions are clearly observed.

ance regions, i.e., the depletion regions of p - n junctions. The voltage drop across the middle p - n junction, which was nominally reverse biased according to a simple circuit model of the p - n - p - n structure as shown in Fig. 5, plays a key role in governing the current leakage over this structure and merits detailed consideration.

Figure 6 shows a measured voltage distribution across the p - n - p - n region of a BH laser under zero bias using the nanopotentiometry technique, together with an SSRM resistance curve across the same area. The peaks of the SSRM resistance curve correspond to the highly resistive depletion regions of p - n junctions. Figure 6 shows that we obtained excellent spatial correlation between the features in the measured voltage data and features in the SSRM resistance curve. Abrupt changes in the slope of the voltage curve are apparent at the interfaces of the p - n junctions. The measured voltage is not uniform across the p - n - p - n region. The voltage profile of the leftmost p -doped layer exhibits a U shape with a bottom at -0.372 V. The voltage in the second p -doped layer increases monotonically from -0.193 to

FIG. 6. One-dimensional voltage profile across the p - n - p - n structure of a BH laser with no bias voltage applied, together with the SSRM resistance curve across the same region. The tip bias was 1.0 V in SSRM measurement.

−0.016 V. The *p*-metal and the two *n*-doped regions remain at constant voltages of −0.007, −0.193, and −0.016 V, respectively.

A voltmeter measures the difference in the free energy between the two contact points. Phenomenologically, the measured voltage V_{measd} can be divided into three components:

$$V_{\text{measd}} = \phi_{c1} + \phi_{12} + \phi_{c2}, \quad (1)$$

where ϕ_{c1} and ϕ_{c2} are the contact potentials at the *p* contact (*c1*) and at the tip (*c2*), see Fig. 1. ϕ_{12} is the potential difference between the two points inside the semiconductor device. When the device is in its equilibrium state (unbiased), the laws of thermodynamics require that the measured voltage V_{equil} must be zero between any cross-sectional points of the structure (provided that the potential of each internal layer of the device is not floating)

$$V_{\text{equil}} = \phi_{c1}^{\text{equil}} + \phi_{12}^{\text{equil}} + \phi_{c2}^{\text{equil}} = 0. \quad (2)$$

As the applied device bias increases from zero, ϕ_{12} , and possibly the contact potentials, deviate from their equilibrium-state values, leading to an output of V_{measd} :

$$V_{\text{measd}} = \phi_{c1}^{\text{bias}} + \phi_{12}^{\text{bias}} + \phi_{c2}^{\text{bias}}. \quad (3)$$

Subtracting Eq. (2) from Eq. (3), we obtain

$$V_{\text{measd}} = (\phi_{c1}^{\text{bias}} - \phi_{c1}^{\text{equil}}) + (\phi_{12}^{\text{bias}} - \phi_{12}^{\text{equil}}) + (\phi_{c2}^{\text{bias}} - \phi_{c2}^{\text{equil}}). \quad (4)$$

It is reasonable to ignore the change of contact potential (ϕ_{c1}) at *c1* since it is closed to a pure ohmic contact and the current flow through the measuring circuit constantly is zero. The contact between the AFM tip and semiconductor surface (at *c2*) is not necessarily ohmic and our previous research indicates it exhibits Schottky-like behavior.²⁶ The difference of contact potential ϕ_{c2} between the biased and unbiased cases may be approximated by a monotonic function $\Delta\phi_{c2}$ of local carrier density *n*. When the carrier density is close to its equilibrium-state value, $\Delta\phi_{c2}$ approximately equals zero. Therefore, the measured voltage can be simplified as

$$V_{\text{measd}} = \phi_{12}^{\text{bias}} - \phi_{12}^{\text{equil}}, \quad (5)$$

where ϕ^{bias} and ϕ^{equil} are the internal potential distribution of the device under bias voltage and equilibrium state, respectively. It is worth noting that Eq. (5) is not likely to apply to the active region of a laser structure under high current injection when the high carrier density effects and many-body effects are expected.

Potential variation across the *p-n-p-n* region under zero bias was observed as shown in Fig. 6. The most likely explanation is that due to the unique properties of the thyristor structure the potential of the internal layers of the structure may be floating. Initially, we felt the observation could partly reflect the built-in electrical field at the *p-n* junctions. However, the built-in voltages across the three *p-n* junctions (from left to right) are calculated according to nominal doping concentrations to be 1.183, 1.17, and 1.188 V, respectively. The disparity between the theoretical prediction and

experimental data suggests other effects may strongly influence the nanopotentiometry measurements. We propose two other possible surface-related effects to explain the zero bias results: the contact potential between the semiconductor and the AFM tip; and the surface potential of the constituent semiconductors.

As shown in Eq. (2), if the built-in potential were not fully compensated by the contact potentials under certain conditions, i.e., the case of the *p-n-p-n* structure, the measured voltage would not be strictly zero. In addition, different contact potentials in various AFM-probe/semiconductor-surface systems were reported by Trenkler and co-workers.¹⁷ By using silicon (Si), metal and two types of diamond-coated Si AFM probes, nanopotentiometry measurements were carried out on a platinum (Pt) and a silicon sample. The authors reported different voltage offsets for the various types of probes up to a positive (on Pt) or negative (on Si) 200 mV. We expect that, similarly, in the nanopotentiometry measurements reported herein, the contact potentials between diamond-coated Si probes and differently doped semiconductors may also vary, leading to different voltage offsets in different regions.

The semiconductor surface states present another important issue in surface characterization using nanopotentiometry. Surface states are the results of the termination of a three-dimensional crystal potential at an exposed plane.²⁷ Such effects may be associated with the changes in the potential due to relaxation, reconstruction, surface defects, or adsorbed impurities.²⁸ The resultant energy levels are primarily localized within the band gap of the bulk band structure. The movement of free charge carriers into the existing surface states is associated with band bending near the surface. As a consequence, the surface Fermi level E_f is pinned at the surface states energy levels.

Experimental measurements^{29–32} reveal the position of the pinned Fermi level at InP surfaces to be strongly influenced by the surface crystal orientation, doping types of the semiconductor, and the preparation of the semiconductor surface. Using x-ray photoelectron spectroscopy, Lau and co-workers³³ found the surface Fermi levels of the *n*- and *p*-type InP were at 0.4 and 0.7 eV below the conduction-band minimum. Measurement of the Schottky barrier height between Au and the cleaved (110) surface of InP also revealed a difference of 0.24 eV between *n*- and *p*-type InP.³⁴ Semiconductor surface states may thus alter the surface potential profiles as obtained in nanopotentiometry measurements relative to bulk potential distributions.

As an empirical way of accounting for our zero-bias results, we propose to subtract the zero-bias data from the biased data to obtain a better approximation to the actual change in the potential distribution upon applying an external bias to the device. This seems to be a reasonable first step, although we can not give full theoretical justification.

We measured the voltage profiles across the *p-n-p-n* region of a BH laser under different biases from zero to above-threshold forward biases. Nanopotentiometry measurement results show that the accumulated voltage drops (from

FIG. 7. One-dimensional voltage profiles across the p - n - p - n region of a BH laser under forward bias voltages.

p -metal to n^+ substrate) measured under different bias voltages are in excellent agreement with the external biases applied to the BH laser samples. Figure 7 shows one-dimensional voltage profiles across the p - n - p - n region of a BH laser under different bias voltages from 0 to 0.977 V. The potential is invariant across each individual n -doped InP layer. Both voltages decrease as the applied bias increases in such a way that the voltage of the rightmost n -InP layer drops faster than the middle n -InP layer. A substantial voltage drop is visible at the interface of p -metal and the leftmost p -InP in curves of all biases. As the external bias exceeds 0.760 V (resultant current is 2.6 mA), abrupt changes in voltage become noticeable at the interfaces of the three p - n junctions.

In order to see the net change in the potential distribution, the unbiased voltage curve was subtracted from each of the biased voltage profiles, as shown in Fig. 8. At small biases, a sudden voltage change appears at the interface of the p -metal with the leftmost p -InP layer. As further bias is applied, substantial voltage drop occurs across the interfaces of the leftmost and rightmost p - n junctions. As the external bias exceeds 0.812 V, abrupt changes in voltage become noticeable at the interfaces of the three p - n junctions. The junction voltage changes saturate under large bias voltages (≥ 0.950 V) at about 0.12, -0.11 , and 0.18 V from left to right. In a

FIG. 8. Subtracted plot for biased-unbiased of one-dimensional voltage profiles across the p - n - p - n region of a BH laser under forward bias voltages.

simplified device model (as shown in Fig. 5), we may regard the p - n - p - n thyristor structure as three p - n junctions connected in series (since the thickness of each layer is comparable to or even larger than the typical diffusion length) but the junction direction of the middle one is opposite to that of the other two. The negative voltage change across the second leftmost p - n junction indicates that it was nominally set in forward bias mode according to its own junction direction but in reverse bias mode with regard to the overall current direction through the p - n - p - n structure, blocking current flow through the entire device.

IV. CONCLUSIONS

Two-dimensional nanopotentiometry was used to profile the transverse cross-sectional potential distribution in MQW BH lasers under operating biases. Measured results show a nonmonotonic change in voltage across either the p - n - p - n structures or the MQW active region of the lasers under forward bias voltage close to threshold. Our ability to resolve the MQW active region suggests a 20 nm spatial resolution is attainable. Nanopotentiometry measurements were performed on the p - n - p - n region of a BH laser under different forward biases. The experimental data provides a direct insight into the underlying current-blocking mechanisms of the p - n - p - n thyristor structure. Our results demonstrate the utility of 2D nanopotentiometry to delineate quantitatively the transverse cross-sectional structure of complex two-dimensional devices, such as BH MQW lasers, under working conditions.

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- ¹R. Subrahmanyam, J. Vac. Sci. Technol. B **10**, 358 (1992).
- ²The National Technology Roadmap for Semiconductors (Semiconductor Industry Association, San Jose, CA, 1997).
- ³C. Shafai, D. J. Thomson, M. Simard-Normandin, G. Mattiussi, and P. J. Scanlon, Appl. Phys. Lett. **64**, 342 (1994).
- ⁴P. De Wolf, J. Snauwaert, L. Hellemans, T. Clarysse, W. Vandervorst, M. D'Olieslaeger, and D. Quaeys, J. Vac. Sci. Technol. A **13**, 1699 (1995).
- ⁵P. De Wolf, R. Stephenson, T. Trenkler, T. Clarysse, T. Hantschel, and W. Vandervorst, J. Vac. Sci. Technol. B **18**, 361 (2000).
- ⁶Y. Huang, C. C. Williams, and H. Smith, J. Vac. Sci. Technol. B **14**, 433 (1996).
- ⁷J. J. Kopanski, J. F. Marchiando, D. W. Berning, R. Alvis, and H. E. Smith, J. Vac. Sci. Technol. B **16**, 339 (1998).
- ⁸H. Edwards et al., J. Appl. Phys. **87**, 1485 (2000).
- ⁹P. De Wolf, T. Clarysse, W. Vandervorst, J. Snauwaert, and L. Hellemans, J. Vac. Sci. Technol. B **14**, 380 (1996).
- ¹⁰V. V. Zavayalov, J. S. McMurray, and C. C. Williams, J. Appl. Phys. **85**, 7774 (1999).
- ¹¹J. J. Kopanski, J. E. Marchiando, and J. R. Lowney, J. Vac. Sci. Technol. B **14**, 242 (1996).
- ¹²P. De Wolf, M. Geva, C. L. Reynolds, T. Hantschel, W. Vandervorst, and R. B. Bylisma, J. Vac. Sci. Technol. A **17**, 1285 (1999).
- ¹³P. P. Lu et al., J. Vac. Sci. Technol. B **19**, 1662 (2001).
- ¹⁴D. Ban, E. H. Sargent, St. J. Dixon-Warren, T. Grevatt, G. Knight, G. Pakulski, A. J. SpringThorpe, R. Streater, and J. K. White, J. Vac. Sci. Technol. B **20**, 2126 (2002).

- ¹⁵V. V. Zavyalov, J. S. McMurray, S. D. Stirling, C. C. Williams, and H. Smith, *J. Vac. Sci. Technol. B* **18**, 549 (2000).
- ¹⁶T. Trenkler, P. De. Wolf, W. Vandervorst, and L. Hellemans, *J. Vac. Sci. Technol. B* **16**, 367 (1998).
- ¹⁷T. Trenkler, R. Stephenson, P. Jansen, W. Vandervorst, and L. Hellemans, *J. Vac. Sci. Technol. B* **18**, 586 (2000).
- ¹⁸E. Oesterschulze and R. Kassing, Proceedings of the XVI International Conference on Thermoelectrics, Dresden, Germany, 1997.
- ¹⁹*Electric Force Microscopy, Support Notes* (Digital Instruments, Santa Barbara, CA, 1996), pp. 230–231.
- ²⁰M. Nonnenmacher, M. P. O'Boyle, and H. K. Wickramasinghe, *Appl. Phys. Lett.* **58**, 2921 (1991).
- ²¹T. Mizutani, M. Arakawa, and S. Kishimoto, *IEEE Electron Device Lett.* **18**, 423 (1997).
- ²²I. M. P. Aarts and E. H. Sargent, *IEEE J. Quantum Electron.* **36**, 496 (2000).
- ²³St. J. Dixon-Warren, R. P. Lu, S. Ingre, D. Macquistan, T. Bryskiewicz, G. Smith, and B. Bryskiewicz, *J. Vac. Sci. Technol. A* **19**, 1752 (2001).
- ²⁴N. Tessler and G. Eisenstein, *IEEE J. Quantum Electron.* **29**, 1586 (1993).
- ²⁵D. Ban and E. H. Sargent, *IEEE J. Quantum Electron.* **36**, 1081 (2000).
- ²⁶R. P. Lu, K. L. Kavanagh, St. J. Dixon-Warren, A. J. SpringThorpe, R. Steater, and I. Calder, *J. Vac. Sci. Technol. B* **20**, 1682 (2002).
- ²⁷C. G. Scott and C. E. Reed, *Surface Physics of Phosphors and Semiconductors* (Academic, New York, 1975), pp. 96–140.
- ²⁸M. Prutton, in *Surface Physics*, Oxford Physics Series, edited by D. J. E. I. E. J. Burge, and J. A. D. Matthew (Oxford University Press, London, 1975), pp. 62–78.
- ²⁹W. M. Lau, R. N. S. Sodhi, and S. Ingre, *J. Vac. Sci. Technol. A* **6**, 1371 (1988).
- ³⁰W. M. Lau, R. N. S. Sodhi, and S. Ingre, *Appl. Phys. Lett.* **52**, 386 (1988).
- ³¹K. A. Stair and Y. W. Chung, *Phys. Rev. B* **32**, 3904 (1985).
- ³²M. Yamada, A. K. Wahi, T. Kendelewicz, and W. E. Spicer, *Phys. Rev. B* **45**, 3600 (1992).
- ³³W. M. Lau, R. N. S. Sodhi, S. Jin, S. Ingre, N. Puetz, and A. SpringThorpe, *J. Appl. Phys.* **67**, 768 (1990).
- ³⁴S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981), p. 291.