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Potential imaging of operating light-emitting devices using Kelvin force microscopy

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We report on the measurements of two-dimensional potential distribution with nanometer spatial resolution of operating light-emitting diodes. By measuring the contact potential difference between an atomic force microscope tip and the cleaved surface of the light emitting diode, we were able to measure the device potential distribution under different applied external bias. It is shown that the junction built-in voltage at the surface decreases with increasing applied forward bias up to flatband conditions, and then inverted. It is found that the potential distribution is governed by self-absorption of the sub-band-gap diode emission. *© 1999 American Institute of Physics.*
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The shrinkage of semiconductor devices to the submicrometer level has led to the need for the direct measurement of two-dimensional (2D) potential profiles with nanometer resolution. A combination of scanning Kelvin force microscopy (KFM) and atomic force microscopy (AFM) has already been demonstrated as a powerful tool for conducting such measurements. Due to its promise of high-spatial-resolution surface potential measurements, the KFM has found many diverse applications in just a few years. Nonenmacher *et al.* have applied the technique to materials work function mapping.[1] Kikukawa *et al.* have conducted surface potential measurements of silicon pn junctions,[2] Vatel and Tanimoto have demonstrated potential measurements of resistors,[3] and n-i-p-i heterostructures.[4]

Although KFM has proved to be effective in electrical characterization of devices, to date there are very few reports[5] of potential profiles of operating semiconductor devices, i.e., measurements conducted under external applied bias. The information given by such measurements (which has not been available up to now in the submicrometer scale), is useful for understanding the relations between the device performance and surface band structure. The surface band structure has a large effect on physical device properties like carrier recombination,[6] and breakdown phenomena. Therefore KFM measurements can lead to improved understanding of the performance of surface rich devices like light-emitting diodes (LED's) and semiconductor lasers. In this work, we report on measurements of 2D potential distribution of operating GaP LEDs. It is shown that the junction built-in voltage at the surface (V_{bi}^{s}) decreases with increasing applied forward bias up to flatband conditions, and then inverted. By measuring current–voltage ($I-V$) and light–voltage ($L-V$) characteristics of the device, it is shown that the potential distribution is governed by self-absorption of the sub-band-gap LED emission.

Figure 1 shows a schematic diagram of the KFM measurement setup. It is based on a commercial AFM (Autoprobe CP, Park Scientific Instruments, Inc.) operating in the non-contact mode. For topographic imaging, the cantilever, heavily doped silicon with sharpened tip (<20 nm radius), was driven by a piezoelectric bimorph at a frequency slightly above resonance. An alternating voltage $V_{\mathrm{ac}}\sin(\omega t)$ at a frequency of around 20 kHz was applied to the cantilever in order to induce an alternating electrostatic force between the tip and the sample. The contact potential difference (CPD) between the tip and the sample surface was measured in the conventional way by nullifying the output signal of a lock-in amplifier (LIA) which measures the electrostatic force at the frequency ω^1. The sensitivity of the surface potential measurements was evaluated by applying an external step voltage to the sample and measuring the CPD between the tip and the sample during a line scan. The sensitivity was better than 5 mV for an applied V_{ac} of 5 V. The measured CPD was independent of: (i) the ac bias amplitude (V_{ac}), (ii) the frequency of the applied ac bias (as long as it was above 20 kHz), and (iii) of the distance between the vibrating tip and the sample surface which was usually on the order of $10-20$ nm.

The GaP samples (Elma Inc.) were grown by liquid phase epitaxy. They consisted of a 10 μm thick Zn-doped ($p \simeq 5\times10^{17}$ cm^{-3}) GaP layer on top of a 40 μm thick n-type layer grown on a GaP substrate; the peak emission was at a wavelength of 565 nm. Ohmic contacts were formed using evaporation of Ni/Ge/Au/Ni/Au to the n-type substrate,

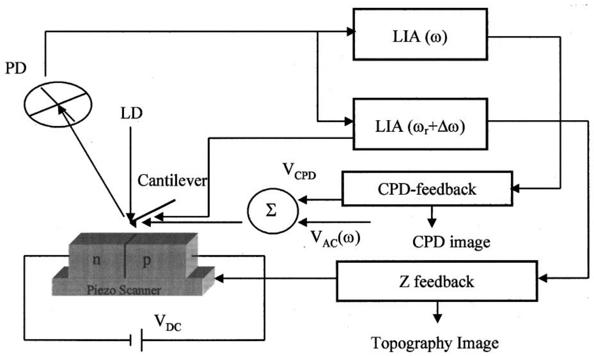

FIG. 1. Schematic diagram of the KFM measurement system. LD—laser diode, PD—photodiode, LIA—lock-in amplifier.

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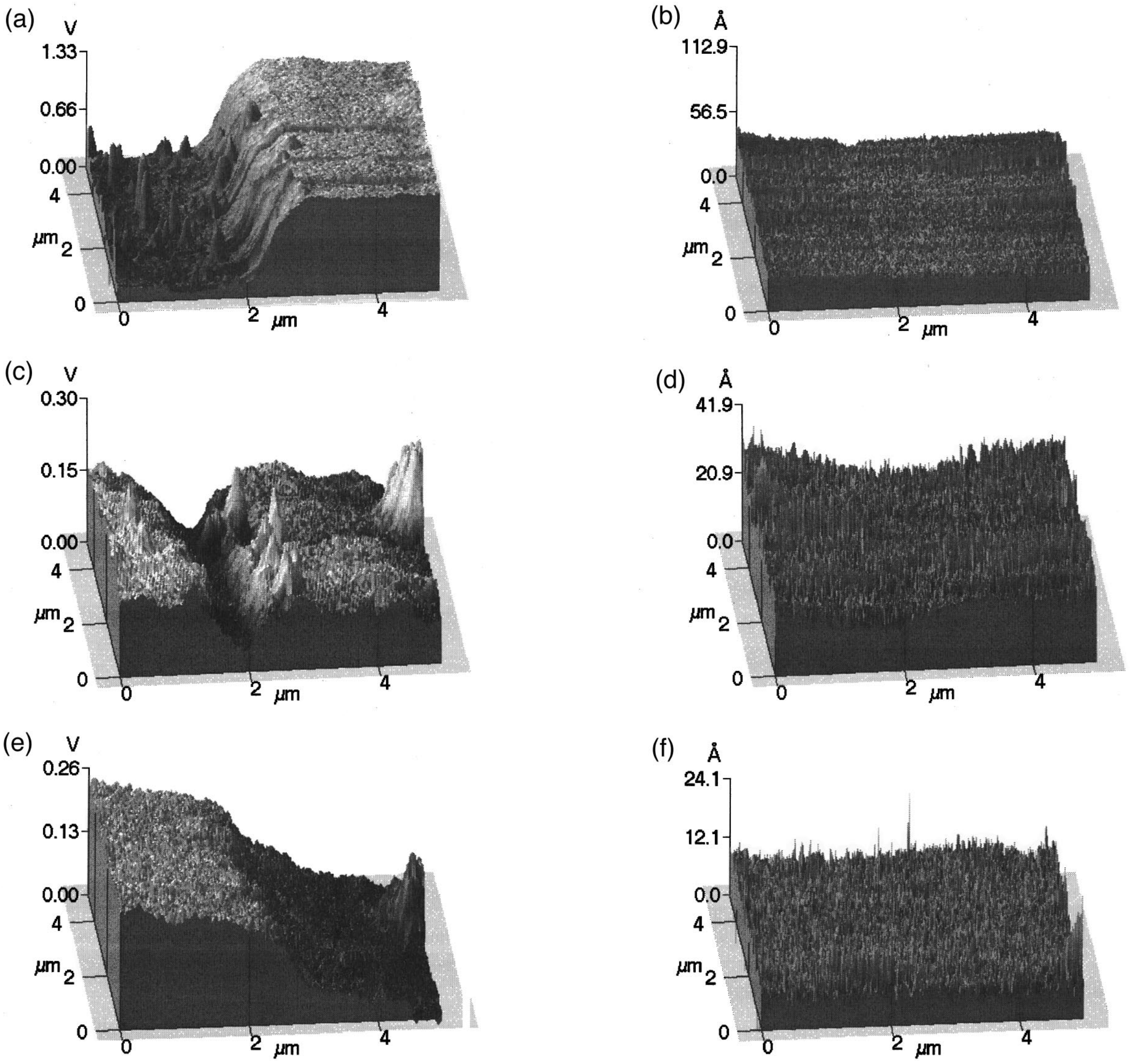

FIG. 2. CPD and topography images of the cleaved LED. Structure measured in equlibrium (a),(b) under applied bias of 1.66 V (c),(d) and 1.78 V (e),(f). The topographic images (b), (d), and (f) demonstrate that there is no ''crosstalk'' between the van der Walls and electrostatic forces.

and Pd/Zn/Pd for the top *p* layer. The samples were cleaved in air, and then placed in a specially designed holder for the KFM measurements. The bias to the LED was applied in the way shown in Fig. 1.

Figure 2 shows CPD (a), (c), and (e), and noncontact topographic images (b), (d), and (f) measured simultaneously on the GaP cleaved structure in (a), (b) equilibrium (no external applied bias), (c), (d) under an applied forward bias of 1.66 V, and (e), (f) an applied forward bias of 1.78 V. Note the different vertical scales in (a), (c), and (e). V_{bi}^{s} measured with no external bias is larger than 1.2 V [Fig. 2(a)]; this V_{bi}^{s} is lower by about 0.8 V than the theoretical built-in voltage, calculated for the sample doping levels. The lower V_{bi}^{s} is most probably due to two main reasons: semiconductor surface states, and/or external charge on the sample surface. Surface states (due to imperfect cleavage and/or oxides on the air-exposed sample) can trap holes (electrons) on the cleaved surfaces of the $p(n)$ sides of the junction creating depletion-type band bending opposite in sign on each side of the junction. Thus the bands will bend up in the *n*-doped region and down in the *p*-doped region, with the net result being a reduction of V_{bi}^{s}.

As the p-n junction is forward biased, V_{bi}^{s} is reduced until flatting of the surface p-n junction is achieved at an applied bias of 1.66 V [Fig. 2(c)]. When the forward bias is further increased, V_{bi}^{s} changes sign [Fig. 2(e)]. Examination of all the topographic images in Fig. 2 shows that the applied bias does not affect the topographic images; this means that the Van der Walls and the electrostatic forces are very well separated by the two feedback circuits. Figure 3 shows CPD line scans measured across the cleaved p-n junction at nine different external biases. The main feature evident from this figure is that V_{bi}^{s} changes by 1.1 V (from 900 to −200 mV) for an external bias change of only 0.28 V (1.5 to 1.78 V). This phenomenon is explained below.

In principle, a change in V_{bi}^{s} which is much larger than the external applied bias can be due to two reasons: (1) Reabsorption of light emitted inside the device, (2) charging or discharging of surface states. Changes in V_{bi}^{s} resulting from light absorption are due to electron transfer from a shallow state located at an energy of $E_t = 2.2$ eV below the conduction band minimum (E_c), to the conduction band. Such a transition increases the band bending at the *p*-layer surface (due to an increase of the free electron concentration in the

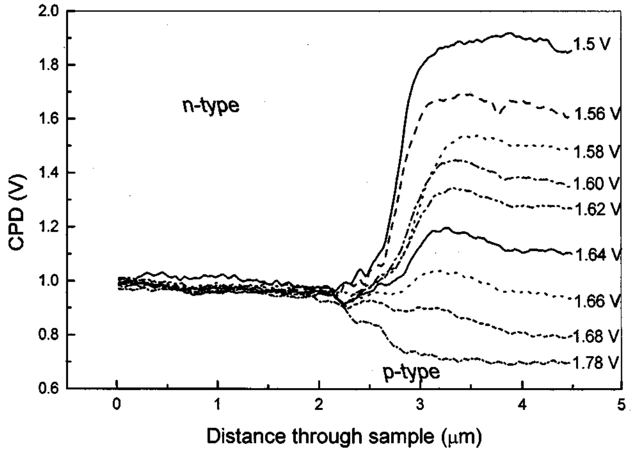

FIG. 3. Potential distribution across the p-n junction under nine different applied forward bias.

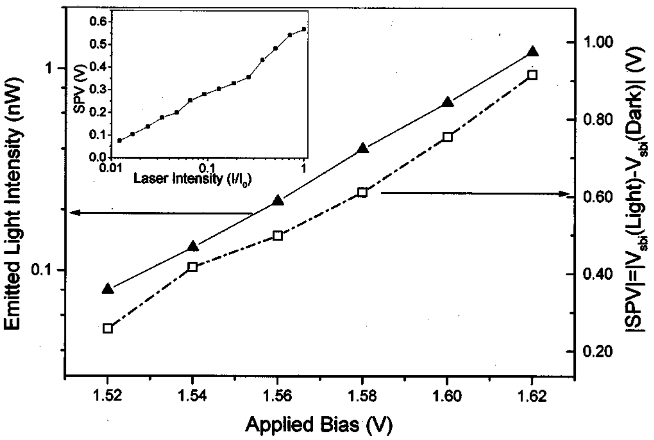

FIG. 4. Changes in V_{bi}^{s} (right), together with the measured LED emission (left) as a function of the applied forward bias. The insert shows changes in V_{bi}^{s} measured under external illumination.

conduction band) thus decreasing V_{bi}^{s}, as explained earlier. This transition was observed by conventional surface photovoltage measurements conducted on the p side of the junction.[7]

The second possibilty that the changes in V_{bi}^{s} are due to changes in the surface charge density is rejected due to the following argument. Under forward-applied bias, the n-type and p-type cleaved surfaces are driven into depletion as observed by the decrease in V_{bi}^{s}. Under such conditions, the minority carrier concentration at the surface increases. If these minority carriers will be trapped by surface states, the band bending on both the n and p sides of the junction will decrease; this is because the surface states are occupied by the majority carriers in depletion. A reduced band bending (*weaker* depletion) on the n and p sides of the junction will increase V_{bi}^{s} as explained previously. However, the experimentally observed decrease of V_{bi}^{s} means that changes in the surface charge density due to such processes are negligible relative to the changes in V_{bi}^{s} caused by the self absorption phenomenon as discussed below.

In order to verify that the changes in V_{bi}^{s} resulting from optical absorption, we have measured the changes in V_{bi}^{s} induced by external illumination. This was done by exciting the cleaved junction using an argon ion laser ($\lambda = 488$ nm) passing through an optical fiber brought to a distance of about 100 μm from the AFM tip. The measured changes in V_{bi}^{s} are shown in the insert to Fig. 4. The highest light intensity ($I/I_0 = 1$) corresponds to an estimated photon flux of tens of μW/cm^2 reaching the GaP surface underneath the tip. This light intensity changes V_{bi}^{s} by about 0.5 V. A very similar dependence is observed in the main plot of Fig. 4 which shows the changes in V_{bi}^{s} ($|SPV|$) as a function of the external applied bias. The internal light intensity, L (shown on the left), was measured by placing a very sensitive laser power meter (PD UV 300, Ophir Inc.) above the cleaved junction. The graph shows that a V_{bi}^{s} change of $\simeq 0.65$ V is caused by a change in the internal light intensity by a factor of 24. This is in fair agreement with the results obtained under external illumination, where a change of 0.5 V in V_{bi}^{s} is caused by a change of a factor of 80 in the external light intensity. In addition, the observation that $|SPV|$ changes linearly with the external applied bias supports our hypothesis that the changes in $|SPV|$ are due to the absorption of the internal LED emission. This is because $|SPV|$ is proportional to $\ln(L)$ (Ref. 8) which is proportional $\mathrm{Ln}(I)$ that is proportional to the applied bias, V_{applied}. Thus we conclude that the large changes of V_{bi}^{s} and the junction reversal as a result of the applied bias, is a result of a photovoltage change induced by the LED internal emission.

In summary, we have demonstrated the use of Kelvin force microscopy to 2D potential measurements of operating light-emitting devices. We were able to image the operating device surface band structure with nanometer resolution, and to show that it is governed by the internal light emission.

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