Noninvasive optical probe of free charge and applied voltage in GaAs devices

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We have demonstrated an application of a noninvasive optical probe that can independently measure both free sheet charge density and applied voltage in GaAs devices. Large-signal direct-current measurements of voltage and charge were made on a Schottky diode without any assumption of the device parameters. The measurements are reproducible, and no adjustable parameters have been used to quantitatively measure charge and voltage. In addition to a lateral charge resolution, given by the beam spot size, we have observed a longitudinal resolution due to the standing wave in the probe beam.

The noninvasive optical probe, the charge sensing probe, based on the detection of free-carrier optical dispersion using 1.3 μm laser light, was originally developed by Heinrich *et al.*[1] for silicon devices. We have adapted this technique to the measurement of both charge and voltage in GaAs devices. In contrast to voltmeters and capacity-voltage (*C-V*) meters used for charge and voltage measurements of devices, the optical techniques are noncontact, are noninvasive even at microwave frequencies, can probe within devices and at internal nodes within integrated circuits, and can potentially provide subpicosecond time resolution by using pulsed laser probes. These probe features are important in the development of high-performance devices such as resonant tunneling diodes and quantum well devices, where our understanding of the device physics is less mature, and an experimental technique to directly access the internal parts of a device is highly desirable.

The charge-voltage probe (Fig. 1) is an optical interferometer. Light from a 1.3 μm wavelength laser passes through a Nomarski prism which splits the light into two perpendicularly polarized beams emerging with a 2.4 mrad angular separation. The two beams cross approximately 25 mm after the Nomarski prism at the focal plane of the lens. Both beams are focused through the polished backside of GaAs substrate and are reflected internally from the front surface of the chip. In a charge measurement, the "probe" beam passes through a device in which the charge density is electrically varied, and the "reference" beam passes through an inactive region in the chip. The free charge present in the active device perturbs the index of refraction and induces a change in the phase of the optical beam. Consequently, the phase of the probe beam is modulated relative to the reference beam by a change in charge density. The two reflected beams return through the substrate and are recombined in the prism. A polarizing beamsplitter converts the phase modulation into an amplitude modulation which is then detected by a germanium photodiode receiver circuit. Because the crossing point of the two beams after the Nomarski prism is in the front focal plane of the lens, a full overlap of the two reflected beams is possible, which gives the system better performance in signal strength and absolute calibration. The probing wavelength of 1.3 μm is far from the plasma resonant frequency and also far below the GaAs bandgap energy; so the absorption losses are very low. Additionally, deep level absorption by the EL2 transition in GaAs is negligible at this wavelength.[2] The electrical input applied to the device is square-wave modulated and a lock-in detection is used to improve the signal-to-noise ratio. Furthermore, because of the chopping, we are not sensitive to any static changes in the refractive index.

When both beams pass through the active region of the device, the phase difference between the two beams arises from the linear electro-optic effect alone and the probe measures the integrated voltage difference along the probe path. The electro-optic signal is maximized by aligning the polarization of the two orthogonally polarized beams with the birefringent axes introduced by the electric field. The applied peak-to-peak voltage is determined by

$$V_{\rm pp} = \frac{\pi}{2\sqrt{2}} \frac{1}{k_0 n_0^3 r_{41}} \frac{V_{\rm out}}{A_v R_L I_0}, \qquad (1)$$

where $V_{\rm out}$ is the measured optical signal at the lock-in amplifier, k_0 the free-space probing wave number, n_0 refractive index, r_{41} the electro-optic coefficient, A_v the voltage gain in our receiver electronics (23.1), R_L the load resistor in the germanium photodiode receiver circuit (1.05 kΩ), and I_0 the dc photocurrent. The factor of $\pi/\sqrt{2}$ in Eq. (1) is a consequence of driving the device with a square-wave voltage and using a lock-in amplifier which measures the rms value of the first harmonic of the square-wave signal. The additional factor of 1/2 is due to the double pass of the probe beam through the device. For charge measurements it is necessary to null out the electro-optic signal by a 45° rotation of the probe

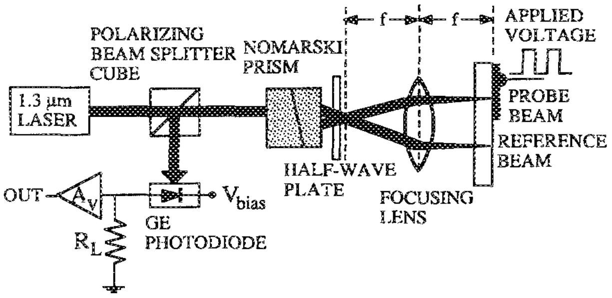

FIG. 1. Schematic diagram of an improved optical charge-voltage probe using a Nomarski prism.

beam polarizations from the maximized signal position with a half-wave plate. The applied voltage does not affect the refractive index at these polarizations. The extinction ratio of the maximized and the minimized electro-optic signal was better than 30:1. Figure 2 shows the electro-optically measured voltage on a reverse-biased Schottky diode with the half-wave plate adjusted for maximized and minimized signal using Eq. (1), and a measured photocurrent of 0.58 mA and a lock-in time constant of 300 ms. The mean value of a series of such measurements taken over several weeks was varied by only 1% from the actual applied voltage, and the standard deviation was 10%. One drawback of voltage measurements with the charge sensing system is that the metal contact on the frontside needs to be at least as large as the spot separation. However, by replacing the Nomarski prism with an appropriate wave plate, the charge-voltage probe is easily converted into the internal electro-optic probe[3,4] measuring voltage with a single probe beam. Calibration of the probe in this case is also given by Eq. (1).

The density-dependent refractive index in silicon is described by the plasma effect.[1,5] For a 1.32 μm probing wavelength the change in the refractive index in n-type GaAs due to the plasma effect is $\Delta n_p = -3.595\times 10^{-21} N_e$ [cm^{-3}], with N_e the free-electron density. The plasma effect describes the contribution to $n(\omega)$ of the intraband transitions (transitions within the same band). Gallium arsenide, however, is a direct band-gap semiconductor, and the additional contribution of the density-dependent interband transitions (transition from valence band to conduction band) is also important. The interband transition probability is modified by the band-filling effect (Burstein–Moss shift[6]), and by the screening of the Coulomb potential of electrons and holes. These effects are fully described by a quantum mechanical Green's function theory[7] or the more phenomenological plasma theory[8] (generalized Elliot formula). The Coulomb interaction of an electron-hole pair (exciton) gives rise to a strong below-band-gap absorption (bound exciton) and to an enhancement of the continuum (unbound exciton). The screening of the Coulomb potential decreases the band gap (band-gap renormalization) and the electron-hole interaction. However, the exciton resonance hardly shifts with increased free-carrier concentration, because the shrinkage of the band gap and of the exciton binding energy almost perfectly compensate each other.[7] The screening has negligible effect on the unbound excitons, as a result of the finite buildup time of the screening potential.[9] Because the total absorption strength of the bound excitons is approximately given by the area formed by the exciton binding energy and the height of the continuum at the band gap, the total change in the bound exciton absorption is canceled by the band-gap renormalization. Additionally, with a probing photo energy well below band gap, the detailed structure of the absorption spectrum has negligible influence on the refractive index. Thus the total change in the refractive index is well approximated by the band-filling effect (from the interband transitions) and the plasma effect (from the intraband transitions).

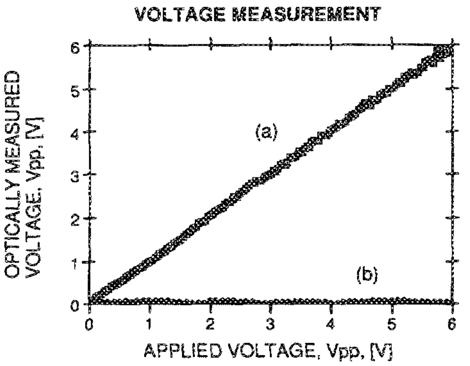

FIG. 2. (a) Result of the optical voltage measurement at maximized electro-optic phase shift with both probing beams passing through the active part of the device. (b) For the later charge measurements (Fig. 3) the electro-optic signal was nulled out by simply rotating the half-wave plate shown in Fig. 1.

The band-filling effect shifts the absorption edge to higher energies because the occupied states near the band minima decrease the transition probability by the Pauli exclusion principle. From the generalized Elliot formula[8] the absorption coefficient changes by a factor $[A(\omega,N) - 1]$, where A is the band-filling factor and N the free-carrier concentration. The change in the refractive index follows from the Kramers–Kronig transformation. For undoped GaAs at room temperature the absorption spectrum close to the band gap has approximately a step-like form,[10] so that the band-gap value α' of about 0.8×10^4 cm^{-1} can be used in the Kramers–Kronig transformation. The refractive index change due to the band-filling effect is then

$$\Delta n_b(E,N_e) \approx -2\frac{\hbar c}{\pi}\alpha' \int_{E_g}^{\infty} \frac{f(\tilde{E},N_e)}{\tilde{E}^2 - E^2}\, d\tilde{E}\,, \qquad (2)$$

with $f(E,N_e)$ the Fermi–Dirac function, E the probe photon energy, N_e the free-electron density, $\hbar$ the reduced Plank's constant, and c the free-space light velocity. For low enough free-electron concentrations the Fermi–Dirac statistic can be approximated by the Boltzmann statistic and the change in the refractive index is then directly proportional to N_e. For a 1.32 μm probing wavelength the change is $\Delta n_b \approx -4.6\times 10^{-21} N_e$ [cm^{-3}].

For charge measurements we place the reference beam outside the Schottky contact (Fig. 1). The electro-optic signal was nulled by adjusting the half-wave plate (Fig. 2). Suppression of the electro-optic signal was experimentally verified by rotating the polarization of the probing beams by 90°, which reverses the sign of the electro-optic signal, but does not affect the charge signal. As the Schottky diode was in reverse bias, thermally induced refractive index changes do not occur. This was experimentally confirmed when the optical signal remained constant as the applied voltage modulation frequency f was varied from 1 MHz to 20 MHz. In contrast, the signal varies as $1/f$ if the optical signal is dominated by the thermal change in refractive index. The Franz–Keldysh effect,[11] which is the solid-state analog of the Stark effect, is proportional to E^2 for photon energies well below band gap, where E is the applied electric field. The Franz–Keldysh effect theoretically should reduce the charge signal at 1 V by 2.4% and at 8 V by about 8%. For a large-signal measurement we drove the reverse-biased Schottky diode by a square wave with a $V_{\rm pp}$ peak-to-peak voltage and a $-V_{\rm pp}/2$ dc bias. Assuming the refractive index change is proportional to the free-carrier density ($\Delta n = n'N_e$), the charge is given by

$$\Delta Q = \frac{\pi}{2\sqrt{2}} \frac{Aq}{k_0 n'} \frac{V_{\rm out}}{A_v R_L I_0}, \qquad (3)$$

using the same notation as in the voltage measurement given by Eq. (1). In addition, n' is the proportionality constant determined by the plasma and band-filling effect ($\approx -8.2\times 10^{-21}$ cm^3), A the Schottky contact area, and q the electronic charge. It is important to note that Eq. (3) is independent of the specific device. Figure 3 shows the total charge difference in the Schottky measured by both a *C-V* meter (solid line) and the optical probe (data points), using Eq. (3) at a photocurrent of 0.49 mA and a lock-in time constant of 300 ms. $V_{\rm out}$ was corrected for the Franz–Keldysh effect. The *C-V* measurement showed that the Schottky diode is, to a good approximation, uniformly doped with a doping density of 2.25×10^{16} cm^{-3}. The periodic variation appearing on the optical measurement arises from the standing wave in the probe beam formed by the incident and reflected beam. The effect of the change in the refractive index on the probe beam is reduced at the nodes and enhanced at the peaks of the standing wave.[12] When the depletion layer edge lies at a node of the standing wave at $V_{\rm pp}$, the free-charge reduction at $V_{\rm pp} + \delta V$ changes the measured signal significantly less than when the depletion layer edge lies at a peak of the standing wave. The observed variation corresponds to a change of the depletion-layer width by $\lambda_n/2$ (0.2 μm), where λ_n is the probe beam wavelength in GaAs. Besides the lateral charge resolution, determined by the beam spot size, this standing wave provides a longitudinal resolution in the device. The standing wave has only small influence on the voltage measurement, because changes in the applied voltage change the electric field across the whole depletion layer width. A series of measurements at an applied voltage of 2 V taken over several weeks showed a mean within less than 1% of the actual charge measured with a *C-V* meter and a standard deviation of 16%.

In summary, we have demonstrated a method for the noninvasive optical measurement of both voltage and sheet charge in GaAs devices. The measurements were quantitative, in good agreement with theory without any fitting parameters, reproducible, and independent of the specific device parameters. We gave a direct relationship between the measured optical signal and the applied voltage and the charge. Besides the inherent lateral resolution of the probe, determined by the beam spot size, the probe has a longitudinal charge resolution due to the standing wave in the probe beam.

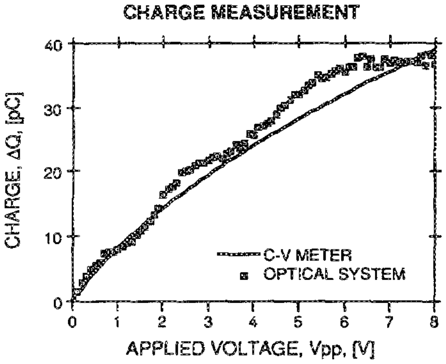

FIG. 3. Experimental charge measurement with both a *C-V* meter (solid line) and the optical charge-voltage probe (data points). The electro-optic signal was nulled out as shown in Fig. 2.

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