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Photoresistivity and photo-Hall-effect topography on semi-insulating GaAs wafers

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By placing a semi-insulating GaAs wafer on a flat, rare-earth magnet, and irradiating the surface with two perpendicular slits of light to form a Greek cross configuration, it is possible to perform photoresistivity and photo-Hall-effect topography on the wafer. The technique is nondestructive in that the contacts are tiny, removable In dots which are placed only on the periphery. By varying the wavelength of the light, selective centers, such as EL2, can be mapped. We compare a $1.1\text{-}\mu\text{m}$, photoexcited electron concentration map with a quantitative EL2 map on a 3-in. undoped, liquid-encapsulated Czochralski wafer.

The process-control requirements for large-area GaAs digital-integrated circuits (IC's) and monolithic microwave IC's demand GaAs semi-insulating (SI) substrate wafers of high lateral uniformity. Thus, methods of measuring lateral uniformity have proliferated during the last five years, and, in fact, whole conferences are now devoted to this subject.¹ The major interest, of course, is in nondestructive techniques, which include photoassisted resistance,²⁻⁶ microwave photoconductance,^{7,8} photoluminescence,^{9,10} cathodoluminescence,¹¹ photoabsorption,^{12,13} and x-ray scattering.¹⁴⁻¹⁶ Unfortunately, however, there are no non-destructive Hall-effect, or even true resistivity, topographic methods being used up to now. The photoassisted resistance technique, first reported by Blunt *et al.*^{2,3} in 1982 (called "dark-spot resistance"), is perhaps the closest in terms of extracted information, although it has the disadvantages of measuring only resistance, not resistivity, and of being unable to provide mobility and carrier concentration information. In this letter, we report a technique for obtaining photo-Hall maps of 3 in. SI GaAs wafers using a powerful, flat, 3 in. magnet and two narrow, perpendicular light slits, forming a Greek cross. The results are compared with EL2 data on the same wafer.

We first discuss the dark-spot resistance (DSR) method,^{2,3} which inspired the present technique. In the DSR method, contacts are placed around the periphery of the wafer, as illustrated in Figs. 1(a)–1(c). Note that the technique is nondestructive only if the contacts can be removed, prior to processing. We find that small In dots can be soldered on the wafer and are ohmic, without alloying. (In highly conductive material, they must be alloyed, of course.) The contacts can then be removed, after the mapping, by a small amount of pressure. A slight residue, if present, should not inhibit subsequent processing since only the outer edge of the wafer is affected. In any case, the residue can be removed with HCl, if desired. We have also successfully used silver paste contacts.

A "slit" of light is now placed on the sample by shining a light beam through a mask. A current forced through a con-

tact at one end of the slit will follow the path of the slit, because SI GaAs is highly photoconductive. A dark spot placed in the slit [Fig. 1(a)] will now absorb most of the voltage drop between contacts, and thus the measured resistance will be representative of the material in the dark spot. By moving the dark spot along the slit, and by rotating the slit itself, the whole wafer can be mapped. Unfortunately, it may not be possible to ignore resistance contributions from the contacts or "arms." Note that if the dark spot is left out then the measured resistance is really a photoresistance, averaged over the whole arm. Although photoresistance is an

FIG. 1. Various experimental configurations for the results reported here. The shaded areas denote darkened surfaces, and the unshaded areas, lighted surfaces. (a) The dark-spot method of Blunt *et al.*, Ref. 2. (b) The Greek cross configuration for photoresistivity, and (c) photo-Hall-effect measurements. (d) A four-contact arrangement for average dark wafer properties. (e) A four-point-probe configuration which has been well studied in the literature. (f) A simulation of (e), although not exactly equivalent, with peripheral instead of interior contacts.

interesting, useful parameter,^{7,8} it cannot be mapped by this method because of the large-area averaging involved, i.e., the whole slit.

Now suppose *two* perpendicular slits of light are placed on the wafer, as shown in Fig. 1(b). The two slits form a classical Greek cross, which has been well studied in the literature.^{17,18} As before, current is confined to the slits by the strong photoconductivity, but now the "active" area is the small square at the intersection of the slits. (It should be emphasized here that this area is photoexcited, not dark as in the DSR method.) Instead of a *resistance*, we are measuring a true *resistivity* ρ of the square portion alone, and ρ will be given by the usual van der Pauw formula¹⁸

$$\rho = \frac{\pi t}{\ln 2} \frac{R_{21,34} + R_{32,41} + R_{43,12} + R_{14,23}}{4} \Omega \text{ cm}, \quad (1)$$

where t is the thickness (cm) of the conductive region, and $R_{ij,kl}$ is the resistance (Ω) measured with current flowing between contacts i and j , and voltage taken across contacts k and l . The polarity of contact i should match that of l , and similarly for j and k . It is clear that the entire wafer can be mapped by moving the light slits around. For accurate measurements, it is necessary to keep the length of the arms larger than their width, i.e., $l > a$.¹⁷ Thus, to map the area near the periphery, the slits should be correspondingly narrow. Corrections due to the asymmetry of the arms will also be small as long as $l/a > 1$ for all four arms.¹⁷

We now propose the most significant use of the geometry in Fig. 1(b), that of Hall effect, illustrated in Fig. 1(c). It is presently possible to purchase¹⁹ commercial, rare-earth, flat magnets of 2 or 3 in. diameter (or larger), and 1/2 in. thickness, which will give 1–2 kG magnetic field strength of sufficient uniformity, except very close to the edge. By placing a wafer on the magnet, the Hall coefficient R_H can be determined from the relationship¹⁸

$$R_H = \frac{10^8 t}{B} \frac{R_{31,42} + R_{42,13}}{2} \frac{\text{cm}^3}{\text{C}}, \quad (2)$$

and, thence, mobility μ and carrier concentration n can be calculated from $\mu = R_H/\rho$ and $n = 1/eR_H$. Here, B is in gauss and t in cm, and we are assuming a unity Hall factor. If desired, current and magnetic field can be reversed, and the data all averaged. However, we have found that these additional measurements are seldom necessary for GaAs.

The experiment described above measures photoconductivity (or photoresistivity) and the photo-Hall effect. The relevant thickness t will therefore be determined primarily by the absorption coefficient of the light α and the carrier diffusion length L . These effects are discussed in detail elsewhere,²⁰ but it should be noted that t can be varied from less than 1 μm up to the total wafer thickness simply by varying the light wavelength. Furthermore, spectroscopy can be performed in the same way, and, e.g., EL2 can be mapped by using a wavelength at which EL2 absorbs strongly. Such capabilities have been exploited in a slightly different way with the dark-spot technique,⁶ but this technique measures neither a true resistivity nor a Hall effect, as explained before.

In this letter, we present data only for below-band-gap excitation, produced by a 600-W tungsten lamp through a Si

filter, which cuts off light with $\lambda < 1.0 \mu\text{m}$. The slits were each 6 mm wide, which produced an "active" area of $6 \times 6 \text{ mm}^2$. Smaller slits could be used to obtain better resolution. The dominant below-band-gap excitation in SI GaAs is due to EL2,²¹ which begins to absorb at $\lambda \sim 1.2 \mu\text{m}$. Thus, the relevant bandwidth is about $0.2 \mu\text{m}$ around a central value of $1.1 \mu\text{m}$. The measured photon intensity I_0 entering the sample was 7×10^{16} photon/cm² s, corrected for the 30% reflection. It is easy to show, for $\alpha L \ll 1$ and $at \ll 1$, that the photoexcited carrier concentration due to EL2 excitation is given by

$$\Delta n = I_0 \alpha_n \tau_n = I_0 (\sigma_{vn} N_{\text{EL2}}^0) \tau_n, \quad (3)$$

where α_n is the absorption coefficient and σ_{vn} is the photon-capture cross section for *electron* excitation, known to be about $9 \times 10^{-17} \text{ cm}^2$ at $1.1 \mu\text{m}$.²¹ (The corresponding quantities for hole excitation are much less important in this experiment.) The neutral EL2 concentration N_{EL2}^0 comprises about 90% of EL2 in this case. We have measured Δn by the photo-Hall method and N_{EL2}^0 by an absorption technique, so that Eq. (3) yields the lifetime τ_n as the only unknown. As an example, in the middle of the wafer, we calculate $\tau_n = 7 \times 10^{-9} \text{ s}$, a typical value for undoped, SI GaAs.

Mapping results for $n(\text{dark})$, $n(1.1 \mu\text{m light})$, $\mu(1.1 \mu\text{m light})$, and [EL2] are shown in Fig. 2. The 3-in. boule was grown by the low-pressure, liquid-encapsulated Czochralski method and three wafers, Nos. 18 (near seed end), 31, and 47 were available for characterization. No. 31 was used for the nondestructive measurements, such as absorption (for EL2) and photo-Hall effect, and the other two wafers were cut into $6 \times 6 \text{ mm}^2$ pieces for dark-Hall effect, mass spectroscopy, and other kinds of measurements. Thus, we cannot directly compare dark-Hall and photo-Hall data; the former are averaged values from wafers 18 and 47. However, we can safely assume that $n(\text{dark}) \leq 5 \times 10^7 \text{ cm}^{-3}$ for wafer 31, also, and therefore $\Delta n = n(\text{light}) - n(\text{dark}) \approx n(\text{light})$. The [EL2] data were obtained from $1.1 \mu\text{m}$ absorption measurements.²¹ It is seen that [EL2] and $n(1.1$

FIG. 2. Comparison of carrier concentration, mobility, and EL2 variations along a [110] direction in a 3-in., undoped SI GaAs wafer.

μm) show the commonly seen "W" shapes, while n (dark) may be a "W" or a "U." The shape of μ is not as evident, although it may be an "M." (It should be noted that the μ 's span only a 7% range, close to the measurement precision.) The average mobility is quite high, about $7.6 \times 10^3 \text{ cm}^2/\text{V s}$, close to the lattice-limited value of about $8 \times 10^3 \text{ cm}^2/\text{V s}$. The average *dark* mobility of wafers 18 and 47 is also high, about $7.4 \times 10^3 \text{ cm}^2/\text{V s}$. These high mobilities are largely due to a low carbon concentration ($\sim 7 \times 10^{14} \text{ cm}^{-3}$), which has the added effect of producing less charged EL2 scattering centers.

As shown in Eq. (3), we expect $\tau_n \propto \Delta n / N_{\text{EL2}}^0$. The shape of τ_n deduced in this way shows no clear pattern, and thus is not shown. It is probable that the "W" shape of Δn (or n) is mostly due to the "W" shape of N_{EL2}^0 . The shape of N_{EL2}^0 , on the other hand, is thought to result from the "W" shape of the dislocation density. However, it is not the purpose of this letter to discuss the details of the shape-producing mechanisms, but to present the mapping method itself.

Finally, it is worthwhile to discuss the possibility of measuring and mapping a true, *dark* (equilibrium) resistivity and Hall coefficient. It is easy to get *average* dark values of ρ , μ , and n , over the whole wafer, with the flat magnet, as shown in Fig. 1(d). Such measurements could be used, e.g., in standard acceptance testing. For mapping, however, we would like an equivalent of the four-point-square-probe technique [Fig. 1(e)], which has been used extensively with conductive Si and Ge, but not GaAs.¹⁸ To properly describe configuration 1(e), Eq. (1) must be augmented by a factor of approximately 2, as is well known from previous studies.^{18,22} The equivalent of configuration 1(e), with peripheral contacts, is shown in Fig. 1(f). Here, very narrow light slits emulate point contacts to the dotted area. However, 1(f) is not exactly equivalent to 1(e) because the light slits produce equipotential lines in the 1(f) configuration which do not exist in the 1(e) configuration. Preliminary experimental results indicate that the mobility measured in 1(e) or 1(f) is smaller than that measured in 1(d) by about a factor of 2. However, this configuration needs to be studied further, both experimentally and theoretically.

By applying small, removable In or silver-paste contacts on the periphery of a semi-insulating GaAs wafer, and two perpendicular slits of light between various groups of four contacts each, it is possible to nondestructively map the photoresistivity and photo-Hall parameters, ρ , μ , and n over the surface of the wafer. The key elements here are a powerful

flat magnet, the Greek cross geometry formed by the two slits of light, and the removable contacts on the periphery. It should be possible to automate this technique by using a probe stage. General, nondestructive screening of whole wafers can be accomplished by placing only four contacts on the periphery, and then measuring the Hall effect in the dark and/or the light with the flat magnet. Also, it is possible to change the conduction depth in the wafer by varying the wavelength of the light; for example, a crude mobility depth profiling could be carried out in this way. A further advantage of varying the wavelength would be that impurity and defect spectroscopy could be performed.

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