Direct measurement of minority carriers diffusion length using Kelvin probe force microscopy

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We report on the use of Kelvin force microscopy as a method for measuring very short minority carrier diffusion length in semiconductors. The method is based on measuring the surface photovoltage between the tip of an atomic force microscope and the surface of an illuminated semiconductor junction. The photogenerated carriers diffuse to the junction, and change the contact potential difference between the tip and the sample as a function of the distance from the junction edge. The diffusion length L is then obtained by fitting the measured contact potential difference using the minority carrier continuity equation. The method is applied to measurements of electron diffusion lengths in GaP epilayers. © *1999 American Institute of Physics.* [S0003-6951(99)03742-0]

Minority carrier diffusion length (L) is an important parameter in determining the performance of minority carrier devices such as solar cells, bipolar transistors, optical detectors, and more. In the past many different techniques have been used to determine L. The three most widely used methods are electron-beam induced currents (EBICs),[1] surface photovoltage (SPV),[2] and photoluminescence (PL).[3]

In the EBIC method (probably the most widely used technique) a p-n junction or a Schottky barrier is viewed edge on. With the scanning electron microscope in a line scan mode, the electron beam scans the semiconductor perpendicular to the potential barrier and generates electron–hole pairs. The generated charge carriers then diffuse to the junction, where the electrons and holes are separated and a current is generated in the external circuit. This current, referred to as the EBIC current, reflects the amount of excess carriers generated. A theoretical fit to the experimentally measured current allows for the evaluation of L. The main disadvantage of the EBIC technique is that the shape of the EBIC curve depends on several factors, most importantly on the surface recombination velocity of the surface on which the beam impinges. Several theoretical models have been derived to overcome this problem.[4]

In the SPV method, a super band-gap energy monochromatic light of a wavelength λ illuminates the semiconductor. The intensity of the light I is changed so the measured SPV (which is proportional to the concentration of the minority carriers available by the surface) is constant. Under certain assumptions[2] an I vs λ curve of the form $I=C[1/\alpha(\lambda)+L]$, where C is a constant, is obtained. Combining the $I(\lambda)$ results with the knowledge of the $\alpha(\lambda)$ dependence enables the extraction of L. Hence the main disadvantage of the SPV technique is that it requires an accurate knowledge of the $\alpha(\lambda)$ dependence of the measured semiconductor. The PL technique is based on measuring the minority carrier lifetime[5] and calculating L based on the measured mobility of the sample.

Recently, near-field optical imaging[6] and other spatially resolved techniques[7] have been used to measure transport in short-carrier diffusion length semiconductors. In this work we report on a new method for measuring very short minority carrier diffusion lengths in semiconductors. The method is based on measuring the SPV between the tip of a Kelvin probe force microscope (KPFM) and the surface of a uniformly illuminated semiconductor junction. The photogenerated minority carriers diffuse to the junction and change the contact potential difference (CPD) between the tip and the sample. The diffusion length L is then obtained by fitting the spatial distribution of the contact potential difference using the minority carrier continuity equation.

Our method is schematically described in Fig. 1. The cleaved or cross-sectioned semiconductor junction is uniformly illuminated from the top using a laser beam ($\lambda = 488$ nm) passing through an optical fiber brought to a distance of about 100 μm from the atomic force microscope (AFM) tip. The distance between the fiber and the sample surface (which is a few nanometers underneath the tip in the noncontact operation mode) is adjusted in order to create a laser spot size much larger than the measured carriers diffusion length. In the measurements reported here a spot size of about 50 μm in diameter was used. The GaP samples used in

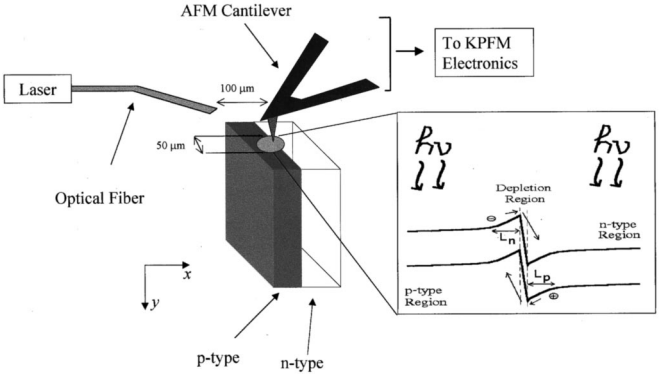

FIG. 1. Schematic diagram of the diffusion length measurement setup. The inset shows the *pn* junction band diagram under illumination, and the minority carrier diffusion to the junction.

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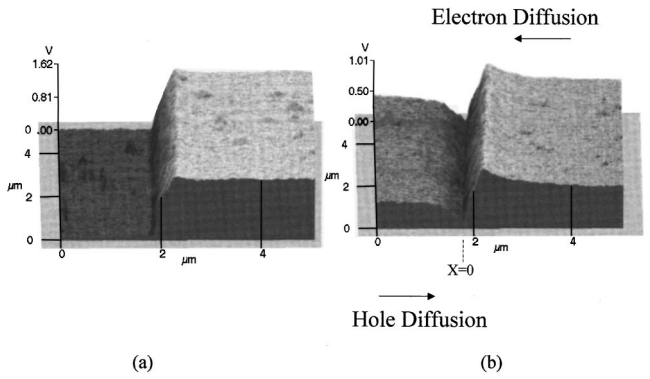

FIG. 2. Two-dimensional CPD images of the cleaved GaP p-n junction in the dark (a), and under super band-gap ($\lambda = 488$ nm) illumination (b). The minority carrier diffusion on both sides of the p-n junction can be clearly observed in (b).

this study (Elma Inc.) were grown by liquid phase epitaxy. They consisted of either $p/n^+/n$ structures of 10–13 μm thick Zn doped GaP $p \cong 5\times10^{17}\,\mathrm{cm}^{-3}$ layer on top of a 40 μm thick n-type layer grown on a GaP n-type substrate. Ohmic contacts were formed using evaporation of Ni/Ga/Au/Ni/Au at the back of the n-type layers, and Pd/Zn/Pd for the top p-type layer.

The KPFM setup is based on a commercial AFM (Autoprobe CP, Park Scientific Instruments, Inc.) operating in the noncontact mode. 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 CPD between the tip and the sample surface was measured in the conventional way by nullifying the output signal of a lock-in amplifier which measures the electrostatic force at the frequency ω.[8,9]

The photogenerated minority carriers change the CPD between the tip and sample by changing the surface band bending. The induced SPV is a function of the excess minority carrier concentration at the surface. Therefore the SPV will be the smallest at the edge of the junction (due to depletion of minority carriers) and will increase with the distance from the junction due to the diffusion of the minority carriers. This is demonstrated in Fig. 2 which shows two CPD images (5×5 μm) of a p-n junction measured in the dark (a), and under super-band-gap illumination (b). It is observed that the junction built-in voltage in (b) is greatly reduced due to the photovoltaic effect. In addition there are two regions in (b) where the SPV increases exponentially with the distance from the junction edges; this is due to minority carrier diffusion to the two junction edges. The bumps in the CPD image measured in the dark [Fig. 2(a)] are due to surface states on the cleaved crystal surface; they are not observed in Fig. 2(b) because of the change in the band bending induced by the illumination.

The calculation of the minority carriers diffusion length from the SPV data is as follows. The dependence of SPV (defined as $|\mathrm{CPD}_{\mathrm{Light}}-\mathrm{CPD}_{\mathrm{Dark}}|$ at the semiconductor surface, $y=0$ in Fig. 1) on Δn [the excess minority carrier concentration at the edge of the space charge region (SCR)] is obtained by measuring it as a function of the exciting light intensity I. The SPV data are then fitted to

$$\mathrm{SPV} = C[\ln(1+I/I_0)], \tag{1}$$

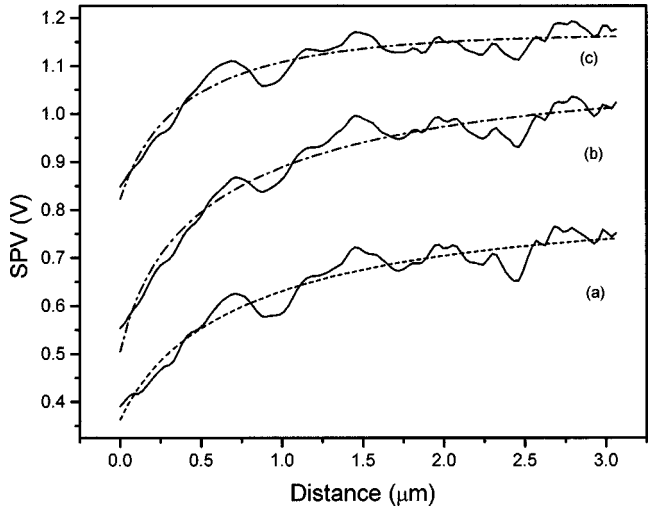

FIG. 3. Experimental (solid lines), and calculated (dashed lines) SPV profiles as a function of the distance from the edge of the p-n junction ($x=0$), for three different light intensities of: (a) 200 μW, (b) 63 μW, and (c) 20 μW at the output of the optical fiber.

which is the equation frequently used to relate the SPV to super band-gap illumination.[10] I_0 is an arbitrary light intensity used for normalization, and C is a constant needed for units conversion. Since Δn is linear with the exciting light intensity $(I)^2$, Eq. (1) represents the dependence of SPV on Δn. Thus, the SPV can now be obtained by calculating Δn using the minority carrier continuity equation and substituting it for I in Eq. (1) above.

The steady state continuity equation for electrons in one dimension (the x axis in Fig. 1), assuming uniform excitation (which is a very good assumption as long as the exciting spot size $\gg L$) can be written as

$$\frac{d^2\Delta n(x)}{dx^2} - \frac{\Delta n(x)}{L^2} = -\frac{g}{D}, \tag{2}$$

where D is the electrons diffusion constant and g is the generation function. Neglecting the electric field in Eq. (2) is justified because Δn is calculated only outside the space charge regions. This also holds for the y direction (perpendicular to the cleaved surface, see Fig. 1) outside the surface SCR, i.e., at a distance of about 50 nm below the cleaved surface. Diffusion in the y direction is neglected because GaP absorption depth $\gg L$ for the laser wavelength used in our measurements. The solution to Eq. (2) subjected to the boundary conditions

$$\left.\frac{d\Delta n}{dx}\right|_{x=0} = \frac{S}{D}\Delta n(x=0); \quad \left.\frac{d\Delta n}{dx}\right|_{x\to\infty} = 0 \tag{3}$$

is

$$\Delta n(x) = A\exp(-x/L) + g\tau, \tag{4}$$

where τ is the effective electron bulk recombination lifetime, and A is a function of the electron velocity S given by

$$A = \frac{-S}{S+D/L}g\tau. \tag{5}$$

By substituting Eqs. (4) and (5) into (1), we obtain

$$\mathrm{SPV} = C\cdot\ln\{1+[A\exp(-x/L)+g\tau]/\Delta n_0\}, \tag{6}$$

where Δn_0 is a normalization factor. S is the electron velocity at the edge of the p side depletion region (at $x=0$, see Fig. 2); this should not be confused with the surface recombination velocity at the top cleaved surface.

Figure 3 shows experimental (solid lines) and calculated (dashed lines) SPV line scans measured under three different light intensities of: (a) 0.41, (b) 1.3, and (c) 4.1 μW at the output of the optical fiber. The coordinate $x=0$ corresponds to the edge of the depletion region [see Fig. 2(b)]. The highest light intensity is estimated to be not more than a few $\mu W/cm^2$ exciting the sample surface under the tip. This corresponds to $\Delta n < 1\times10^{12}\,cm^{-3}$, which means that all our measurements are conducted under very low injection levels. A nonlinear fit of the data to Eq. (6) with $D=3\ cm^2/s$, gives L of 0.85 ± 0.01, 2.1 ± 0.02, and $2\pm0.02\,\mu$m, and S of 1.7×10^5, 2.5×10^5, and 1.3×10^5 cm/s for Figs. 3(a), 3(b), and 3(c), respectively.

Two important advantages of our method are that the measured diffusion lengths are independent of the surface recombination on the cleaved surface, and of the minority carrier velocity S. The surface recombination will affect the value of $\Delta n(x)$ at the edge of the surface SCR [$x=0$, Fig. 2(b)]; the larger the surface recombination, the smaller the SPV. S will change the constant A in Eq. (5), but not the decay profile of the SPV, which is governed by L. In addition, carrier diffusion towards the cleaved surface will affect the value of SPV, and thus is taken into account in our analysis.

The fits in Fig. 3 show that: (1) The values of L are not very sensitive to the injection levels and (2) the value of S can be obtained from the measurements. The diffusion lengths are in excellent agreement with literature reported values for GaP; these vary between 0.5 and 5 μm depending upon doping and growth methods.[11] EBIC measurements conducted on the same sample gave diffusion lengths in the range 0.5–1.5 μm, for exciting electron beam energies between 5 and 30 kV.[12] However these diffusion lengths are smaller than the electron generation volume at these energies, i.e., below the resolution of the EBIC technique. This emphasizes the main advantage of the method proposed here: the ability to measure very short diffusion lengths (as short as 100 nm), depending on the resolution of the KPFM measurement setup.

In conclusion, we have demonstrated a new method for measuring minority carrier diffusion lengths, based on Kelvin force microscopy. The main advantages of the proposed method are that it can be used to measure very short diffusion lengths, and that L can be obtained explicitly using a very simple analysis.

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