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DETERMINATION OF THE ORIGIN OF THE SERIES RESISTANCE THROUGH ELECTROLUMINESCENCE MEASUREMENTS OF GaAs AND $Al_xGa_{1-x}As$ SOLAR CELLS AND LEDS

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Abstract—A simple method to determine the origin of the total series resistance in GaAs and AlGaAs solar cells and LEDs is given. It allows to discriminate between series resistance effects due to the emitter resistivity and parasitic resistance effects mainly due to the metal–semiconductor contact and the metal of the grid. The method consists of fitting the current–voltage and light intensity–current characteristics. The former is affected by the total series resistance and the latter just by the series resistance due to non uniform current distribution.

1. INTRODUCTION

The reduction of series resistance effects to a minimum is a key issue in the design of solar cells. In LEDs such a reduction is important to minimize losses in the emitted light intensity at high currents. The sources of the total series resistance can be separated into a parasitic resistance mainly due to the metal–semiconductor contact and the metal of the grid, and a series resistance due to the emitter layer. The latter produces a non uniform current distribution through the device. The parasitic resistance can be minimized by proper fabrication technology and the non uniform current distribution by an appropriate front contact design. The ability to discriminate between both components would allow improvements in the design of the device.

We present here a simple method to distinguish between the aforementioned components of the total resistance. The only characterization necessary is the measurement of the current–voltage and light intensity–current characteristics. The first characteristic is affected by the total series resistance and the second one just by the series resistance due to the emitter. The expression for the current–voltage characteristics is well known. A simple model to obtain the analytical expression for the current dependence of the light intensity is given. We obtain the value of the total series resistance by fitting the current voltage characteristics and the series resistance due to the emitter by fitting the light intensity–current characteristics. The parasitic resistance is then given by the difference between the two values.

2. THEORETICAL MODEL

The whole device will be treated as a parallel connection of a specified number of elementary cells as sketched in Fig. 1(a). We restrict the analysis to a simplified structure consisting of an emitter and a base region. We assume that the current I_e flows horizontally in the emitter and the current I_b vertically across the junction and in the base. When the current flows in the emitter, there is a voltage drop in this region due to the presence of the emitter lateral resistance. In Fig. 1(a) we indicate the distributed resistance of the emitter. The diode under the metal D_m is not affected by the resistance of the emitter as can be seen in the figure. The current passing through D_m is I_m. The resistance R_{paras} results mainly from the metal–semiconductor contact and the metal of the grid, but may also include other possible parasitic resistances. We assume that the resistance of the bulk region in the base is negligible.

The current in the device has two components: the space charge recombination current and the diffusion current. The space charge recombination current, I_2, is modelled as[1]:

$$I_2 = I_{02}\exp\left(\frac{qV_j}{2kT}\right) \quad (1)$$

where V_j is the voltage drop across the junction. The diffusion, or recombination in the neutral regions, current I_1, under low injection conditions, is given by Shockley[2] as

$$I_1 = I_{01}\exp\left(\frac{qV_j}{kT}\right) \quad (2)$$

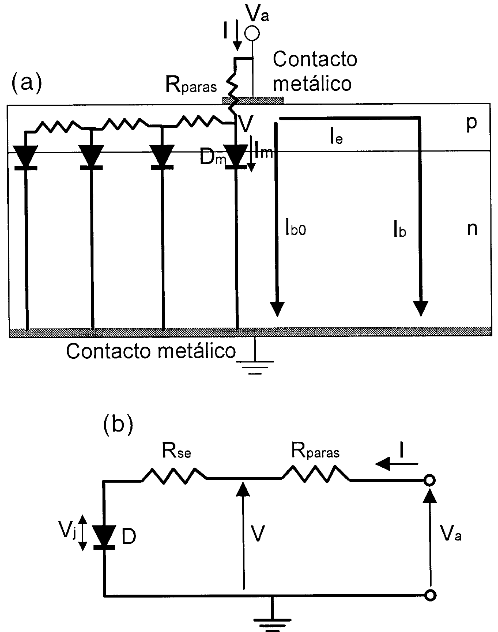

Fig. 1. (a) Cross section of one of the elemental units that constitutes the device. On the right, our assumption as to how the current density flows through the device is shown. On the left, an equivalent circuit is sketched, where I is the total current injected in the device, V_a the applied voltage, V the voltage after the metal–semiconductor contact, I_e is the emitter current, I_b is the current in the base and across the junction, R_{paras} the parasitic resistance due mainly to the metal–semiconductor contact and the metal of the grid. (b) Equivalent circuit of the circuit sketched in (a) with a global lumped series resistance, R_{se}, due to the emitter layer

Therefore the total current takes the form

$$I = I_{01}\exp\left(\frac{qV_j}{kT}\right) + I_{02}\exp\left(\frac{qV_j}{2kT}\right) \tag{3}$$

In device modeling, it is common practice to use the equivalent circuit of Fig. 1(b) in which R_{se} is a global lumped series resistance due to the emitter layer, which includes the metal contact and non-contacted areas[3]. In this case the current–voltage equation takes the familiar form

$$I = I_{01}\exp\frac{V_a - (R_{paras}+R_{se})I}{kT/q} + I_{02}\exp\frac{V_a - (R_{paras}+R_{se})I}{2kT/q} \tag{4}$$

In this equation the effect of the parasitic resistance and the effect of the series resistance due to the emitter are indistinguishable.

The current under the metal I_m (Fig. 1(a)) is

$$I_m = F_m\left(I_{01}\exp\frac{qV}{kT} + I_{02}\exp\frac{qV}{2kT}\right) \tag{5}$$

where $F_m = A_m/A$ and is the fraction of the area covered by the metal.

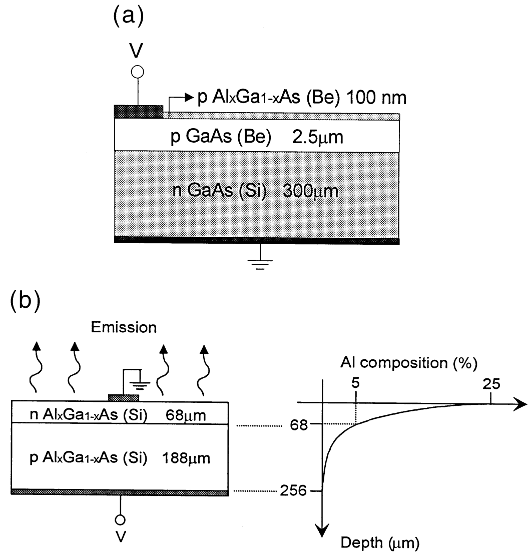

Fig. 2. Structures of the fabricated devices. (a) GaAs solar cell. (b) $Al_xGa_{1-x}As$ LED

Most of the photons that might escape from the device are generated by the diffusion current component[4] flowing under the unmetallized area. Therefore the light intensity emitted by the device L is given by the recombination in the neutral regions under the unmetallized region, which is equal to the recombination in the neutral regions of the whole device (the diffusion current component of Equation (4)) minus the recombination in the neutral regions under the metal (the diffusion current component of Equation (5)). Taking into account that

$$V = V_a - R_{paras}I \tag{6}$$

the light intensity is then

$$L = CI_{01}\left(\exp\frac{V - R_{se}I}{kT/q} - F_m\exp\frac{V}{kT/q}\right) \tag{7}$$

where C is a proportionality constant and V can be obtained from

$$I = I_{01}\exp\frac{V - R_{se}I}{kT/q} + I_{02}\exp\frac{V - R_{se}I}{2kT/q} \tag{8}$$

and is given by

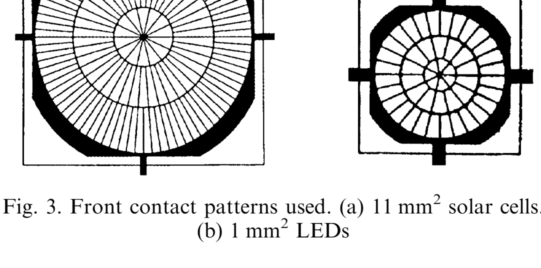

Fig. 3. Front contact patterns used. (a) 11 mm^2 solar cells. (b) 1 mm^2 LEDs

Table 1. Performance parameters of the devices

Device	Type	A (mm^2)	F_m	C (mW/A)	I_{01} (A)	I_{02} (A)	R_{total} (Ω)	R_{se} (Ω)	R_{paras} (Ω)
4J45	Solar cell	11	0.09	12.8	1.9×10^{-20}	7.6×10^{-12}	12.5×10^{-3}	5.5×10^{-3}	7×10^{-3}
R49-7	LED	1	0.15	44	2.0×10^{-22}	1.2×10^{-12}	350×10^{-3}	4.5×10^{-3}	345×10^{-3}

$$V = R_{se}I + 2\frac{kT}{q}\ln\left[-\frac{I_{02}}{2I_{01}}\left(\sqrt{1+\frac{4I_{01}I}{I_{02}^2}}-1\right)\right] \quad (9)$$

The light intensity can then be written as

$$L = C\frac{I_{02}^2}{4I_{01}}\left(\sqrt{1+\frac{4I_{01}I}{I_{02}^2}}-1\right)^2\left[1-F_m\exp\left(\frac{R_{se}I}{kT/q}\right)\right] \quad (10)$$

Therefore the light intensity is not affected by the parasitic resistance R_{paras} but just by the series resistance due to the emitter. We can obtain the total series resistance from Equation (4) and the emitter resistance from Equation (10). The difference will give the parasitic resistance.

This method of separately estimating R_{paras} and R_{se} can identify the main source of resistance in optoelectronic semiconductor devices. This information can then be used to optimize the design of such devices.

The series resistance due to the emitter layer obtained under dark conditions, is in general different from its value under illuminated conditions. At low enough currents, the series resistance under dark conditions, under illuminated and short-circuit conditions and under illuminated and open-circuit conditions converge to a unique value[3]. This value can be used as a reasonable approximation for the practical range of operation of a solar cell, as is discussed in[3]. So the method explained here must be used at low enough currents to get the value of the series resistance. Since the value of the series resistance varies with current this must be obtained within a small range of current where it can be assumed to be nearly constant.

3. EXPERIMENTAL

Solar cells with a structure shown in Fig. 2(a) and light emitting diodes with the structure in Fig. 2(b) have been fabricated. The solar cells consist of a p-$Al_xGa_{1-x}As$/p-GaAs/n-GaAs configuration. The two p-type layers are doped with beryllium and the substrate is doped with silicon. The wafer of LED material was kindly supplied by Sumitomo and processed in our laboratory. The LEDs consist of an $Al_xGa_{1-x}As$ heterojunction doped with silicon in both the p-layer and n-layer. The aluminum composition changes with depth as shown on the right hand side of the diagram. The details concerning device parameters can be found in Table 1. The patterns used for the front metal contact are shown in Fig. 3(a) for the 11 mm^2 solar cells and in Fig. 3(b) for the 1 mm^2 LEDs. The dark current–voltage curves corresponding to a typical GaAs solar cell and a typical $Al_xGa_{1-x}As$

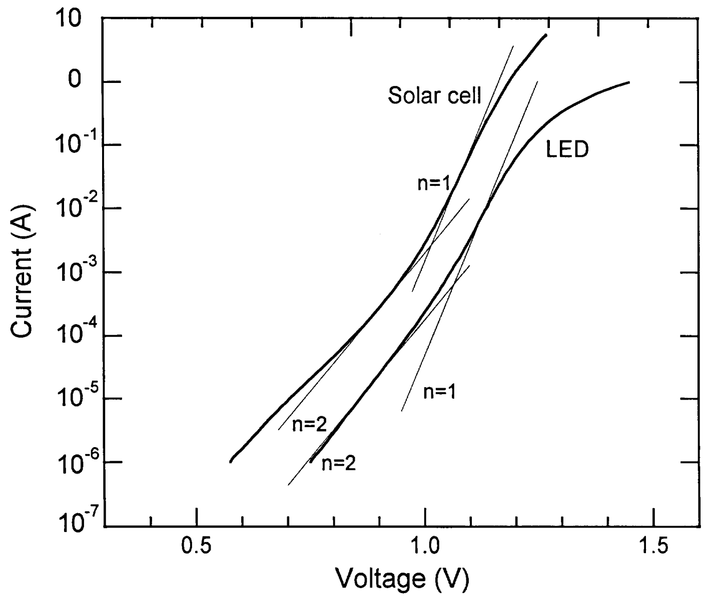

Fig. 4. Current–voltage characteristics of a typical $Al_xGa_{1-x}As$ LED and a typical GaAs solar cell. They show three regions: the first one where space charge recombination current is dominant with an ideality factor of $n = 2$, the second one, characterized by $n = 1$ where the diffusion current dominates and the third one affected by the series resistance effects

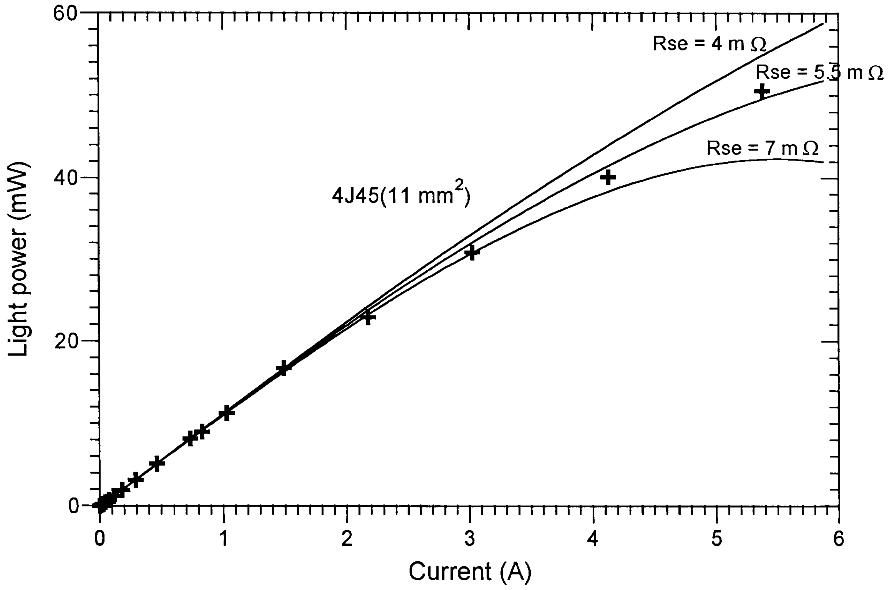

Fig. 5. Light intensity vs current for a typical GaAs solar cell, experimental data (symbols) and theoretical fits (solid line) with parameters in Table 1 and different resistances R_{se}

LED are shown in Fig. 4 with the different regions where the space charge recombination current is dominant ($n = 2$) and the diffusion current becomes relevant ($n = 1$). At high currents the current–voltage characteristic is affected by series resistance effects. By fitting these curves to Equation (4) we obtain the parameters I_{01}, I_{02} and $R_{total} = R_{se} + R_{paras}$ that appear in Table 1.

The total light output was measured using a calibrated large area photodiode. The injected current is continuous at low levels and pulsed (pulse width 1 μs, duty cycle 1%) at high currents to reduce device heating. Heating is also decreased by means of a good thermal contact achieved by soldering the devices onto a copper disk. The light power of a typical solar cell and a typical LED is given in Fig. 5 and Fig. 6 respectively. The measurements are represented by symbols. The theoretical light power curves given by Equation (10) are sketched by continuous lines for different values of R_{se}. It can be observed that there is a satisfactory agreement between experiment and theory and the best values to fit the curves are given in Table 1. The value of the parasitic resistance of the LEDs is high

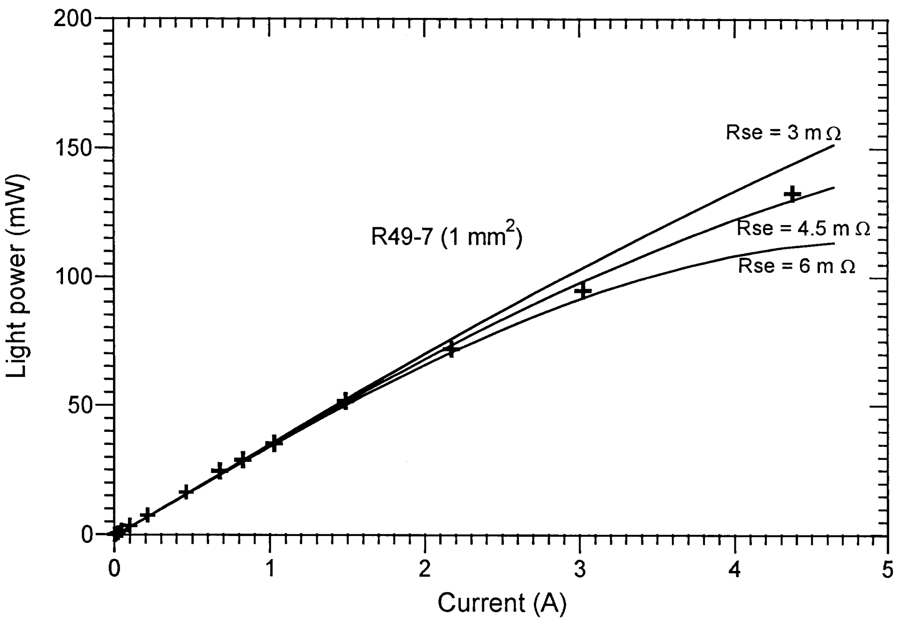

Fig. 6. Light intensity vs current for a typical $Al_xGa_{1-x}As$ LED, experimental data (symbols) and theoretical fits (solid line) with parameters in Table 1 and different resistances R_{se}

due to the high value of the metal–semiconductor resistance with $Al_xGa_{1-x}As$ which increases with aluminum concentration. However in the solar cells devices the parasitic resistance is low because of the better metal–semiconductor contact with GaAs. The value for the series resistance due to the emitter is relatively low in both solar cells and LEDs. The values for the different resistances obtained by fitting the experimental curves agree well with the calculated ones using the equations given in[5].

4. SUMMARY

We have developed a method to obtain the values for the series resistance due to the emitter and the parasitic resistance mainly due to the metal–semiconductor contact and the metal of the grid. A simple model of the current dependence of the light intensity has been presented. Satisfactory agreement between experiment and theory has been demonstrated. The application of the theory to our device leads us to conclude that the value of the parasitic resistance of LEDs is high because of the high value of the metal–semiconductor resistance with $Al_xGa_{1-x}As$. The parasitic resistance in solar cells is low because of the better metal–GaAs contact. The series resistance due to the emitter was found to be relatively low.

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