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Improved Defect Analysis of Gallium Arsenide Solar Cells Using Image Enhancement*

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Summary

A new technique has been developed to capture, digitize, and enhance the image of light emission from a forward biased direct bandgap solar cell. Since the forward biased light emission from a direct bandgap solar cell has been shown to display both qualitative and quantitative information about the solar cell's performance and its defects, signal processing techniques can be applied to the light emission images to identify and analyze shunt diodes. Shunt diodes are of particular importance because they have been found to be the type of defect which is likely to cause failure in a GaAs solar cell. The presence of a shunt diode can be detected from the light emission by using a photodetector to measure the quantity of light emitted at various current densities [ref. 1]. However, to analyze how the shunt diodes affect the quality of the solar cell the pattern of the light emission must be studied. With the use of image enhancement routines, the light emission can be studied at low light emission levels where shunt diode effects are dominant.

Introduction

Shunt defects are imperfections which lower the current through the junction of a solar cell by providing an alternate path for the light generated current to flow. As the solar cell model shows (figure 1), shunt defects may be modeled as resistors or as diodes. Shunt defects are most commonly thought of as light independent conductances caused by depressions, impurities, voids, or dirt on the top layer or surface of the solar cell. However, a shunt defect may also be modeled as a diode having exponential characteristics. The shunt diodes are in parallel with the junction diode which will affect the overall value of the saturation current. Shunt diodes can be caused by various means in the space charge regions including deep level traps, dislocations, variations in doping, and Schottky barriers at the junction. Because shunt diodes follow the exponential diode equation, a variable light intensity plot of the open circuit voltage versus the natural log of the short circuit current ($V_{oc} - ln(I_{sc})$) is used to identify the presence of such diodes. Ideally, the solar cell would not contain any shunt diodes and the slope of the $V_{oc} - ln(I_{sc})$ curve would be constant. The presence of a shunt diode produces regions on the curve with different slopes because the shunt diode has different parameters than the junction diode. The relationship between V_{oc} and I_{sc} can be seen in the solar cell current and voltage equations (eqs. 1 and 2).

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$$I = I_0(e^{\frac{qV}{nkT}} - 1) - I_L \tag{1}$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{sc}}{I_0} + 1\right) \tag{2}$$

The slope of the $V_{oc} - ln(I_{sc})$ curve is proportional to the n parameter of the diode. A shunt diode has a larger effect of the solar cell's response at low output light intensities (low currents). At high light intensities, the junction diode dominates and the shunt diode is not noticeable. The transition of the shunt diode's effect on the solar cell's response as the current and light intensity increase is reflected by the changing slope of the $V_{oc} - ln(I_{sc})$ curve. At low currents, the shunt diode has a lower resistance than the junction diode. Because the diodes are in parallel, more current will flow through the shunt diode than the junction diode. The decrease in current through the junction diode causes the open circuit voltage to decrease. However, the amount that V_{oc} decreases is small because, from equation (2), V_{oc} is proportional to the natural log of I_{sc}. The small change in the current causes an even smaller change in the voltage. Therefore, the presence of a shunt diode is difficult to detect by standard I–V analysis.

Light Emission From GaAs Solar Cells

A solar cell is a p-n junction designed to absorb light, generate minority carriers, and collect them efficiently. A light emitting diode (LED) is also a p-n junction device which, under a forward bias, produces light. The main difference between an LED and a solar cell is the thin top layer of the solar cell. The top layer, the collector, is made thin so the light will not be absorbed but pass through to the active region. A solar cell made from a direct bandgap material (GaAs for example) will emit light under a forward bias. The thin top layer allows the generated light to pass through to the surface.

It has already been shown that the forward biased light emission of a direct bandgap solar cell provides a quick and simple method of testing for the presence of shunt defects [ref. 2]. Because the light emission is caused by the injected minority carrier current, it is very sensitive to any defects which affect the current through the junction. The pattern of light emission shows the overall quality of the solar cell by displaying those areas which do not emit light. The light emission may also be quantized by using a detector solar cell to measure the amount of light emitted. By using a Si detector solar cell, the transition point of the shunt diode's effects on the performance of the solar cell was found to be around $J_{sc} = 0.25$ ma/cm^2. Therefore, to view the effects of the shunt defects, the solar cell must be biased with a very low forward current so the shunt diode will dominate over the junction diode [ref. 3].

Image Enhancement of Light Emission

The amount of light generated with a forward current of less than 1 milliampere (equivalent to $J_{sc} = 0.25$ ma/cm^2 for the 4 cm^2 GaAs solar cells used) is very small. The light may be quantized in order to detect its presence, but this does not provide any localized or qualitative information about the shunt defects. By observing the light emission from several GaAs solar cells, it was found that the light became visible at a forward current of around 4 milliamperes. At this level of current, the junction diode is dominating and the shunt diode's effect may not be noticeable. Therefore, to view the effects of the shunt diode, the solar cell should be biased below the visible threshold and the light emission must be enhanced to be able to view it.

Our new technique involves the use of precise optics with a short focal length to image the light emission on a CCD detector array. Enhancement of the image is done using signal processing techniques. The light emission is digitized by an IBM PC computer which produces a processable image. The image can then be enhanced with several processing routines such as noise reduction, enlargement, histogram equalization for image contrast, and color mapping. The images can be printed on a laser printer for hardcopies or viewed on a display monitor for faster, interactive processing. Figure 2 is the medium-level light emission from a GaAs solar cell biased at the visible threshold without any image enhancement. (The terms low-level, medium-level, and high-level light emission refer to the light emission below, at, and above the visible threshold respectively.) The image is mostly black because the amount of light at the threshold is very small. The light emission shows the grid lines (dark horizontal lines) but does not show any discernible defects. Figure 3 is the medium-level light emission at the visible threshold after the image was processed. The enhanced image shows several defects which were not apparent without the enhancement. This demonstrates the usefulness of the image enhancement routines for defect analysis.

Figure 4 is the high-level light emission. Comparison of the light emission at the high-level and the medium-level reveals similar defects (locations of dark areas). Figure 5 is the high-level light emission after image enhancement. Again, the enhanced image reveals more defects than were apparent before the enhancement. Now comparing the enhanced high-level light emission with the enhanced medium-level light emission, the high-level light emission shows more defects. This exemplifies the difference between the levels of light emission and how the defects vary depending on the current density through the solar cell.

Figure 6 is the low-level light emission after image enhancement. The low-level light emission before enhancement was not included because the image was entirely black. The light emission was not perceivable because it was below the visible threshold. After the enhancement, the appearance of horizontal grid lines became visible. This again demonstrates the advantage of the image enhancement programs. The ability to analyze the light emission will not be limited by visual perception, but can be increased by the enhancement programs.

Conclusions

Shunt diodes have been found to be the type of defect which is likely to degrade and cause failure in solar cells. Because the shunt diodes affect the solar cell's response at very low levels of current, standard I–V analysis is ineffective in determining their presence. Additionally, standard I–V analysis does not provide any localized information about the defects. Light emission has been demonstrated to be an effective method for determining the presence and location of shunt defects. However, at the low levels of current needed to allow the shunt diode to dominate over the junction diode, the light emission is too low to study qualitatively. The image enhancement allows for a better study of the low-level light emission by making the light visible. Therefore, it is now possible to study the shunt diode's effects on the light emission and, more importantly, use the low-level light emission to analyze the shunt diode's effect on the solar cell. Since the shunt diodes are the likely cause of failure in GaAs solar cells, these techniques can be used to predict durability.

References

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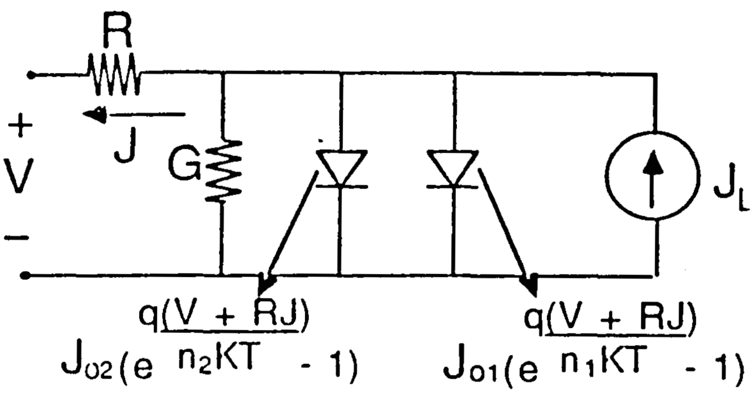

Figure 1. Equivalent circuit model of a solar cell.

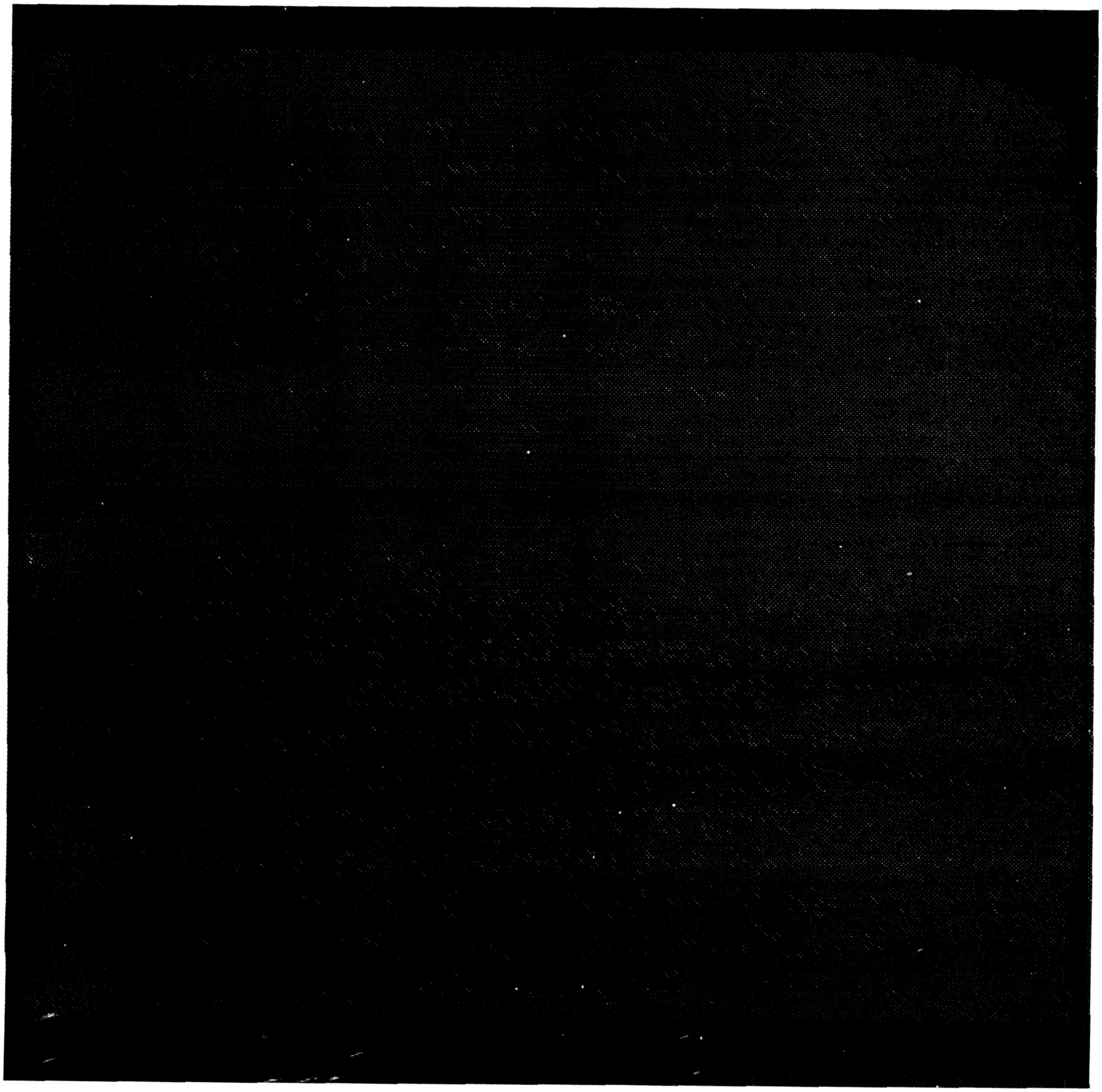

Figure 2. Medium-level light emission before image enhancement.

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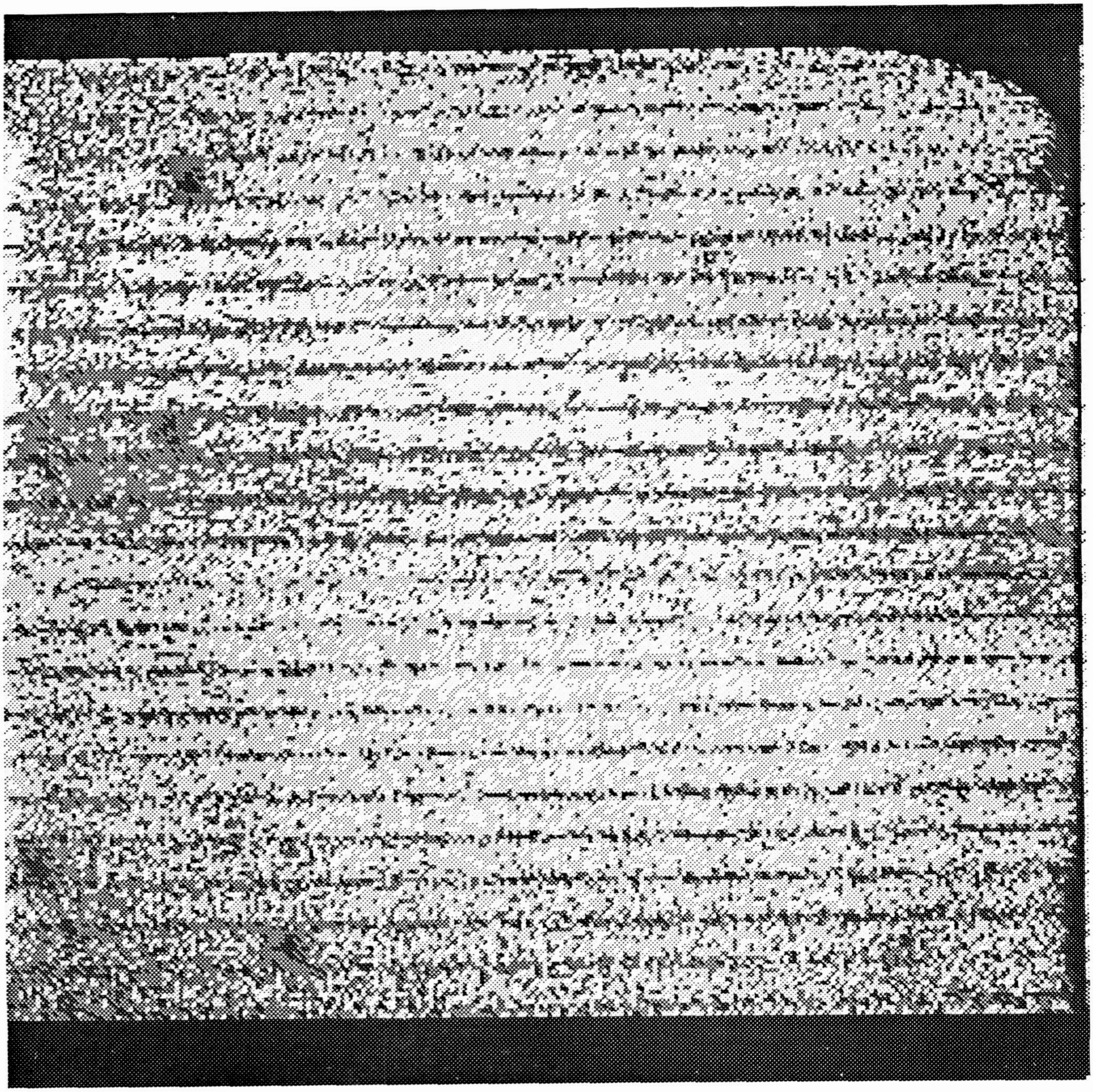

Figure 3. Medium-level light emission after image enhancement.

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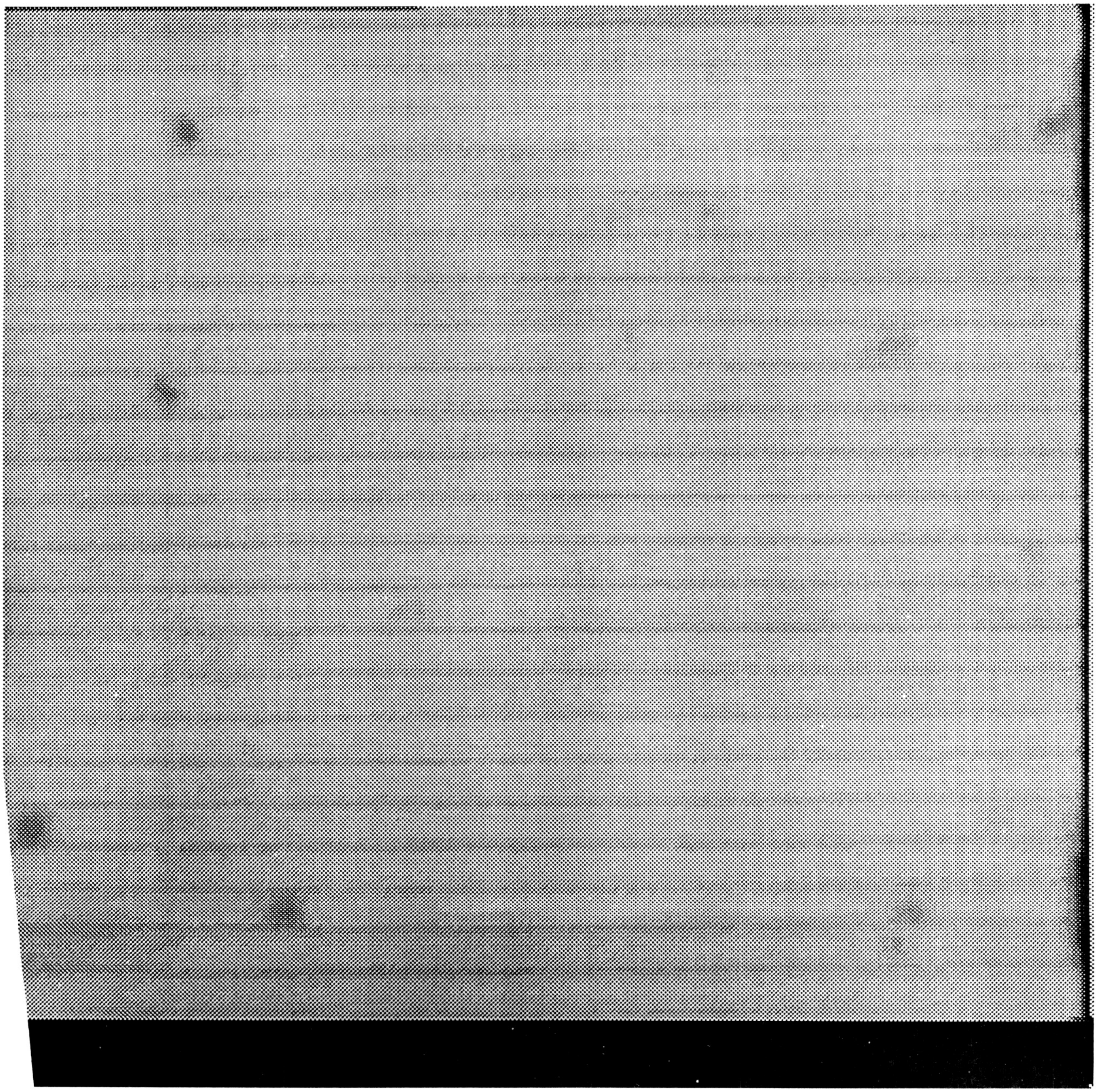

Figure 4. High-level light emission before image enhancement.

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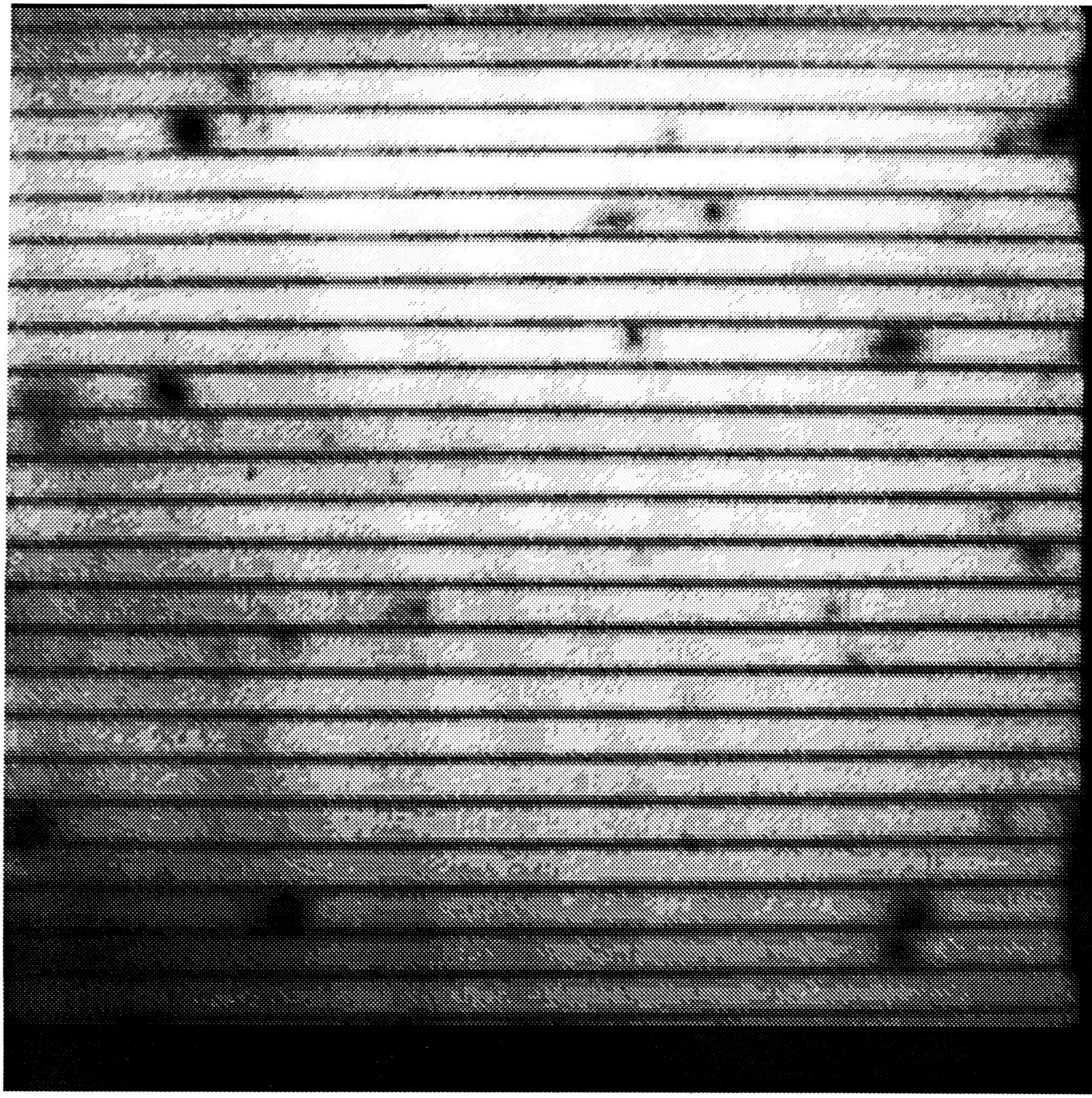

Figure 5. High-level light emission after image enhancement.

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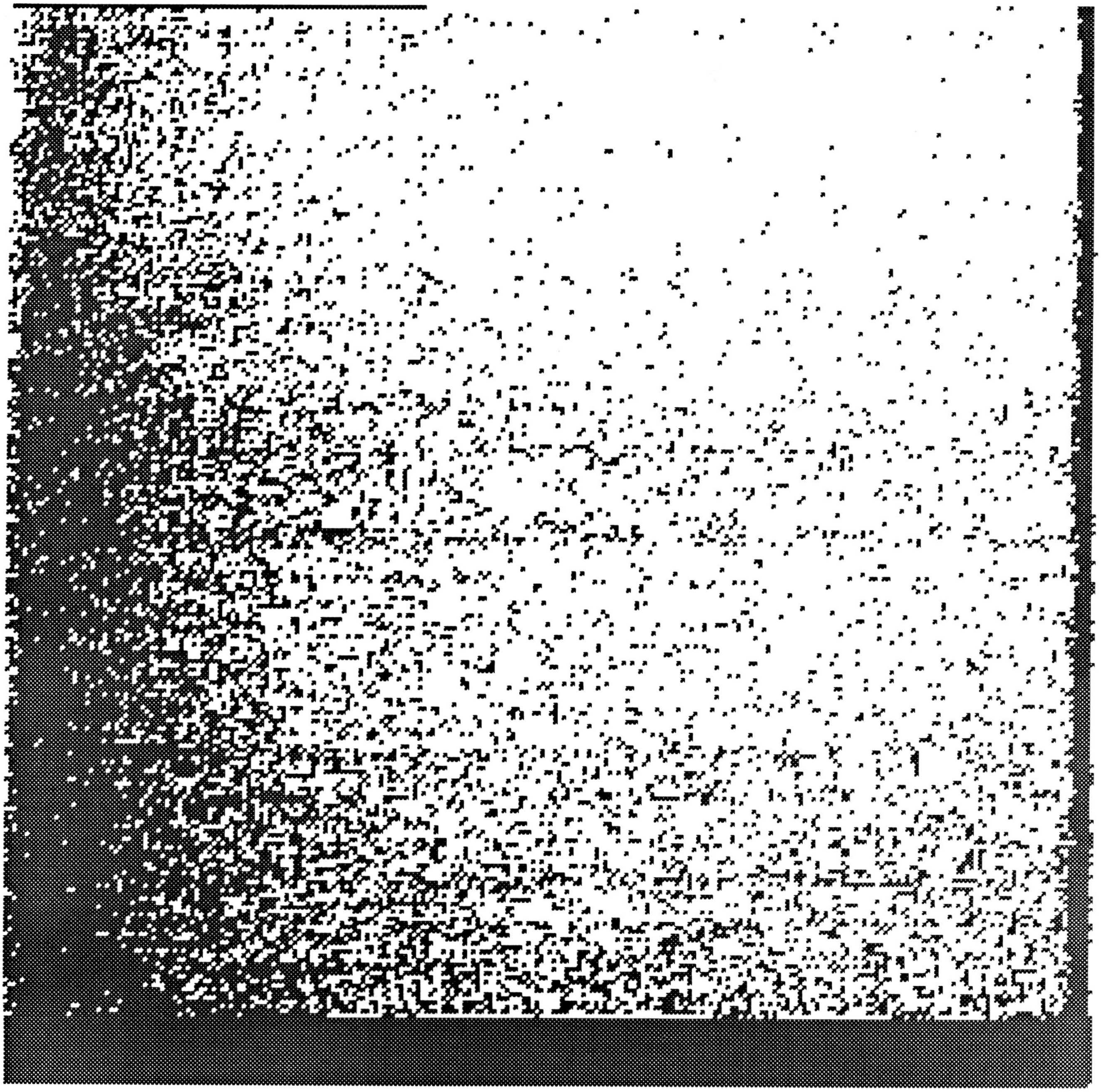

Figure 6. Low-level light emission with image enhancement.

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