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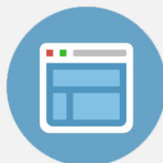
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A phenomenological model for the reliability of GaAs based heterojunction bipolar transistors

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We present a phenomenological model for the lifetime prediction of GaAs based heterojunction bipolar transistors (HBTs). Both thermal activation process and recombination enhanced defect generation process were considered phenomenologically. At high stress temperatures, the lifetime of the transistor is determined by the thermal activation process and is independent of the stress current. But at low stress temperatures, the device's lifetime is controlled by the recombination enhanced defect generation process and is dependent on the stress current. The model has been used to fit experimental data, and very reasonable agreement was obtained. The model is valid for all stress temperatures and stress currents. It provides a good guideline for projecting HBTs lifetimes using accelerated stress test. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2917069]

I. INTRODUCTION

GaAs based heterojunction bipolar transistors (HBTs) have been widely used in high speed wireless and optical communication systems as well as in military and space applications. HBTs' reliability, although extensively studied, remains to be a puzzling issue, not because the devices are unreliable but because of the variation in the reported data.[1–11] The reported activation energy for device degradation varies from below 0.5 eV to nearly 2 eV and the projected mean time to failure (MTTF) also varies in a wide range. While detailed failure mechanisms are dependent on many factors including epilayer quality, process stability, and device design, the various test conditions used by different researchers also create uncertainties in the reported results. Since a device's lifetime, which is projected based on accelerated stress test performed at high temperatures, is impossible to verify experimentally, one really needs a good model to guide the prediction of the tested results. In this paper, we present a simple phenomenological model for HBTs' reliability and clarify some of the inconsistencies in the reported results.

II. DEFECT GENERATION AND DEVICE FAILURE

We assume that the failure of an HBT is caused by defect generation in the device. The defects in turn cause an increase in base current and degradation in current gain. The defects are assumed to be generated by two mechanisms: Thermal activation and recombination enhanced defect reaction (REDR). While the first one is easy to understand, the second one is due to the energy released by the electron-hole recombination at the defect sites.[12–14] This recombination-enhanced process has been widely studied and has been known to play an important role in the degradation of optical devices.[14] For HBTs, where carrier recombination is the key to device performance, it has also been shown that REDR is one of the main causes for device degradation.[15–17] The generation rate of the defect can be written as

$$\frac{dN_t}{dt} = \left(\frac{dN_{t1}}{dt}\right)_{\mathrm{rec}} + \left(\frac{dN_{t2}}{dt}\right)_{\mathrm{temp}}, \tag{1}$$

where the first term is due to the recombination enhanced defect generation and the second term is due to the thermal activation process. Instead of going into details of the nature of defects that cause device failure, we consider there is only one type of defect that has an activation energy of ΔE. When there is recombination enhanced process, the generation rate should be proportional to the recombination current. Because of the energy released by recombination, the activation energy is reduced to a smaller value, $\Delta\varepsilon$. Combining these two processes, we obtain the rate equation as

$$\frac{dN_t}{dt} = a\exp(-\Delta E/KT) + bI_{bs}\exp(-\Delta\varepsilon/KT), \tag{2}$$

where I_{bs} is the nonradiative recombination base current at the stress condition. This current (at stress), however, depends on the defect density through the following relationship,

$$I_{bs} = qN_t\sigma v n_p d, \tag{3}$$

where σ is the cross section for carrier trapping, v is the thermal velocity, n_p is the injected electron density in the base, and d is the base width. Since n_p is proportional to the collector current (at stress), I_{cs}, we obtain from Eqs. (2) and (3)

$$\frac{dI_{bs}}{dt} = AI_{cs}\exp(-\Delta E/KT) + BI_{cs}I_{bs}\exp(-\Delta\varepsilon/KT). \tag{4}$$

If the collector current is fixed during stress, we get the solution

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$$I_{bs} = \left(I_{bs0} + \frac{A}{B} e^{-(\Delta E - \Delta \varepsilon)/KT} \right) \exp(B I_{cs} e^{-\Delta \varepsilon /KT} t) - \frac{A}{B} e^{-(\Delta E - \Delta \varepsilon)/KT}, \quad (5)$$

where I_{bs0} is the base current at $t=0$. It also includes the base current that is not affected by the defect generation. So I_{bs} can be regarded as the total base current at the stress condition. Assuming I_{bs} does not change too much, we obtain

$$I_{bs} = I_{bs0} + [A \exp(-\Delta E/KT) + B I_{bs0} \exp(-\Delta \varepsilon /KT)] I_{cs} t. \quad (6)$$

Now when we measure the device $I-V$ (at room temp) to find out whether the device has degraded or not, the change in base current also depends on the trap density the same way as Eq. (3). So we get a time dependent relationship for I_b,

$$\frac{dI_b}{dt} = A I_c \exp(-\Delta E/KT) + B I_c I_{bs} \exp(-\Delta \varepsilon /KT). \quad (7)$$

Notice that the right hand side of the equation is proportional to I_c, the current at measurement, not I_{cs}. The stress current I_{bs} in Eq. (7) is time dependent as shown in Eq. (6). Substituting Eq. (6) into Eq. (7), we get

$$\frac{dI_b}{dt} = A I_c e^{-\Delta E/KT} + B I_c I_{bs0} e^{-\Delta \varepsilon /KT} + B (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) e^{-\Delta \varepsilon /KT} I_c I_{cs} t. \quad (8)$$

The solution for I_b is

$$I_b = I_{b0} + (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) I_c t + \frac{1}{2} B (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) e^{-\Delta \varepsilon /KT} I_c I_{cs} t^2. \quad (9)$$

Here again I_{b0} includes all the base current components that are not affected by the defect generation. The current gain can be obtained from this equation:

$$\frac{1}{\beta} = \frac{1}{\beta_0} + (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) t + \frac{1}{2} B (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) e^{-\Delta \varepsilon /KT} I_{cs} t^2. \quad (10)$$

The percentage change of current gain versus time is then

$$\frac{\Delta \beta}{\beta_0} = \frac{D \beta_0}{1 + D \beta_0}, \quad (11)$$

where

$$D = (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) t + \frac{1}{2} B (A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}) e^{-\Delta \varepsilon /KT} I_{cs} t^2. \quad (12)$$

If we take 20% drop in current gain as the criterion for device failure, we can solve for the device lifetime from Eq. (11),

$$\mathrm{MTTF} = \frac{e^{\Delta \varepsilon /KT}}{B I_{cs}} \left(\sqrt{1 + \frac{B I_{cs}}{2 \beta_0} \frac{e^{-\Delta \varepsilon /KT}}{A e^{-\Delta E/KT} + B I_{bs0} e^{-\Delta \varepsilon /KT}}} - 1 \right). \quad (13)$$

III. DEVICE LIFETIME: DEPENDENCE ON STRESS CURRENT AND ACTIVATION ENERGY

The lifetime shown in Eq. (13) depends not only on the temperature but also on the collector current, I_{cs}, used in the stress test. The expression of MTTF shown in Eq. (13) has a very interesting dependence on stress temperature. When the stress temperature is high, the high activation energy term dominates in the denominator of Eq. (13) and

$$\mathrm{MTTF} \approx \frac{e^{\Delta E/KT}}{4 A \beta_0}. \quad (14)$$

The lifetime does not depend on the stress currents. But when the stress temperature is not very high, the MTTF is reduced to

$$\mathrm{MTTF} \approx \frac{e^{\Delta \varepsilon /KT}}{B \sqrt{2 \beta_0 I_{bs0} I_{cs}}}. \quad (15)$$

The lifetime is governed by the smaller activation energy $\Delta \varepsilon$ and it is dependent on the stress current. This expression has the form

$$\mathrm{MTTF} \propto I_{cs}^{-n} e^{\Delta \varepsilon /KT}. \quad (16)$$

This is actually the same formula that has been found to fit the measured lifetime of HBTs in the presence of the recombination enhanced defect generation.[1,18–20] However, one needs to remember that this only represents the MTTF when the recombination enhanced defect generation dominates the degradation process, which happens at lower stress temperatures. The complete expression for MTTF has to include the thermal activation process, which dominates at higher stress temperatures. In other words, Eq. (16) is valid in a limited temperature range.

From Eq. (15), we can see that the factor n depends on how I_{bs0} is related to I_{sc}. At high stress currents, this factor depends on several factors. The important ones are (1) the Kirk effect, (2) whether there is a potential spike at the base-emitter junction, and (3) the dependence of current gain on temperature rise due to self-heating. So this factor is quite different for AlGaAs HBTs and InGaP HBTs. The stress current used for accelerated life test is usually ≥ 25 KA/cm^2. At such high currents, the current gain drops due to the effects mentioned above. If we look at the Gummel plots, we may notice that the current gain drops very differently for these two types of transistors. Figure 1 shows the base current and the current gain as functions of the collector current for an AlGaAs HBT and an InGaP HBT with an emitter dimension of 2×6 μm^2. The collector structures of the two transistors are the same, but the current gain rolls off very differently. The gain of the AlGaAs HBT drops very quickly with the collector current while that of the InGaP HBT stays more or less the same until very high currents. This difference cannot be explained by the Kirk effect since the collector structures are the same. So, it should be caused by the

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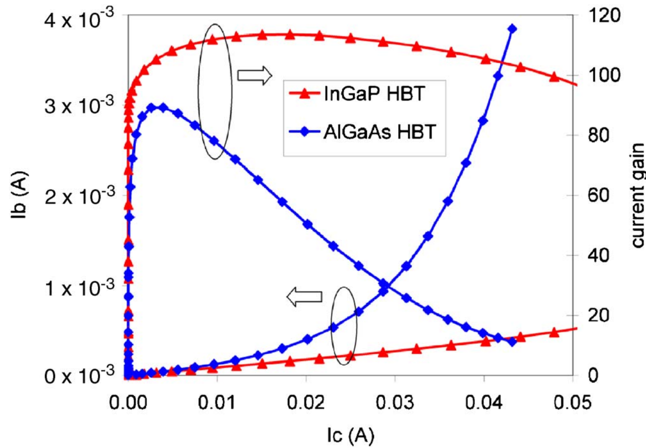

FIG. 1. (Color online) The base current and the current gain as functions of the collector current for an AlGaAs HBT and an InGaP HBT at high currents. The emitter size of the transistors is $2\times 6\ \mu\mathrm{m}^2$.

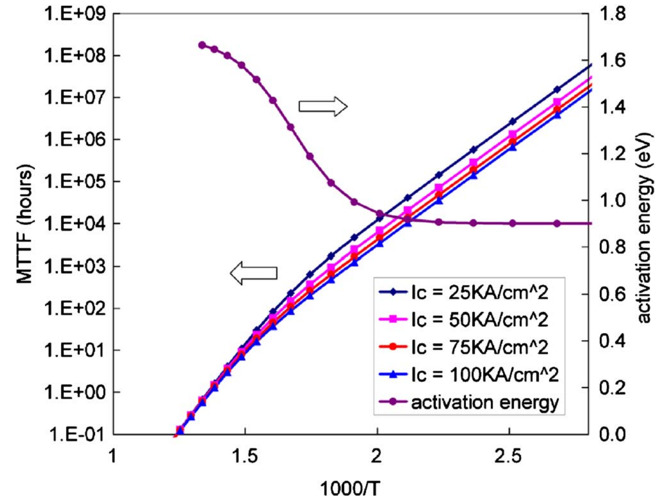

FIG. 2. (Color online) Calculated MTTF as a function of inverse temperature at different stress currents. The activation energy calculated from the curve with a stress current density of $25\ \mathrm{KA/cm^2}$ is also shown in the figure. It is a function of the stress temperature.

other two reasons mentioned above. The dependence of I_b on I_c for the AlGaAs HBT and the InGaP HBT at high currents is very different. If we fit the curve in the high current region for the AlGaAs HBT, the best fit is

$$I_b \propto I_c^3. \tag{17}$$

Substituting this relationship to Eq. (16), we obtain

$$\mathrm{MTTF} \propto I_{cs}^{-2} e^{\Delta\varepsilon/KT}. \tag{18}$$

This agrees with what Henderson has reported experimentally.[18]

For InGaP HBTs, the current gain remains more or less constant at high currents, or I_b is linearly proportional to I_c (see Fig. 1). So, Eq. (15) becomes

$$\mathrm{MTTF} \propto I_{cs}^{-1} e^{\Delta\varepsilon/KT}. \tag{19}$$

This result agrees with the experimental finding by Surridge *et al.*[20] Feng *et al.*, however, reported an n factor of 0.5,[19] which is smaller than what we obtained here. But, the real expression for MTTF, as shown in Eq. (13), is much more complicated. If we want to use a simple expression like Eq. (16) to represent the lifetime, the n factor can be much smaller than 1. Let us use some examples to illustrate this point. Figure 2 shows a set of calculated MTTF vs $1/T$ curves at different stress conditions. Here we assume that I_b is proportional to I_c. The activation energies are chosen to be $\Delta E=1.7$ eV and $\Delta\varepsilon=0.9$ eV. The collector currents used are 25, 50, 75, and $100\ \mathrm{KA/cm^2}$. The current gain is taken to be 70 and assumed to be independent of temperature. Other parameters were chosen so that the calculated results fall in the right range of the experimental results. It is clearly seen that at high temperatures, the degradation is controlled by thermal activation. The activation energy is ΔE and is independent of the stress current. At low stress temperatures, the degradation is controlled by recombination enhanced defect generation, the activation energy is $\Delta\varepsilon$, and the lifetime depends on the current used during stress. It should be noticed that the measured activation energy is usually based on a fitted straight line with only a few data points in the Arrhenius plot. So, depending on where the data are taken on the curves shown in Fig. 2, the activation energy can vary greatly. We have calculated the activation energy based on the slope of the MTTF curves in Fig. 2. The calculated result (for $Jc=25\ \mathrm{KA/cm^2}$), also shown in the figure, varies from ΔE to $\Delta\varepsilon$ depending on where the slope is measured.

At lower stress temperatures, MTTF is I_{cs} dependent and the n factor is 1. But between these two extremes, the dependence of MTTF on I_{cs} is not that simple. If we plot MTTF vs I_{cs} (in log-log plot) at different stress temperatures, we obtain the curves shown in Fig. 3. The n factor varies from 1 to 0 as the stress temperature is increased. This explains why some of the reported values were lower than 1.[19]

The model presented above is a general model. The activation energies and the relative importance of the two mechanisms (thermal activation and recombination enhanced process) depend on the material used, the process techniques, and the device structures. At high stress temperatures, the degradation is determined by the thermal process and does

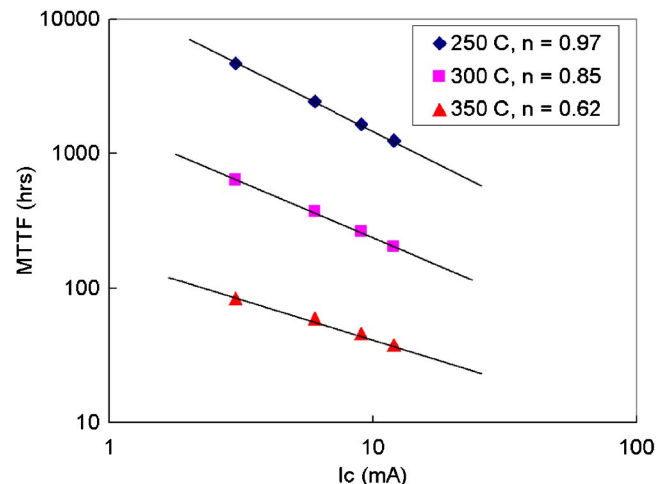

FIG. 3. (Color online) Calculated MTTF as a function of the stress current at different temperatures. This figure shows that the n factor, as seen from the slope of the curves, can change as the temperature changes.

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not depend on the stress current. At lower stress temperatures, the recombination enhanced process dominates and the degradation is dependent on the stress current. The activation energy is lower when the stress temperature is lower and higher when the stress temperature is high. The transition temperature again depends on process and material. This result agrees with what Henderson has found experimentally.[10]

Because of the two mechanisms involved in the device failure and the transition in the Arrhenius plot, one needs to be careful when deducing the activation energy using two or three data points, especially those taken at very high junction temperatures. The extrapolated lifetime at low temperatures can be easily overestimated if a wrong activation energy is used.

From the published reports, the AlGaAs HBTs usually have lower activation energy than the InGaP HBTs and the lifetime is shorter. This can be explained by a lower transition temperature in our model. In other words, the AlGaAs HBTs are more sensitive to the recombination enhanced defect generation. Because of a small valence band offset at the AlGaAs/GaAs junction, the current gain is very temperature sensitive. The base current increases drastically as the stress temperature is increased and it contributes to the reduction of the lifetime [see Eqs. (13) and (15)].

IV. MODEL FITTING TO EXPERIMENTAL DATA

In order to check the validity of this model, experimental data taken at a wide temperature range are needed. To obtain data at very high stress temperatures, we have carried out a wafer level reliability test for our InGaP HBTs at extremely high current conditions.[6] No external heating source was used; the self-heating provided the necessary heating for the device aging. Based on the model presented above, the lifetime should not depend on the stress current used.

The wafer level stress test was done at various bias conditions. The bias currents varied from 167 to 583 $\mathrm{KA/cm^2}$. The bias voltages were kept low so that the devices stayed within the safe operating area. The corresponding junction temperatures were estimated to be all above 350 °C. The lifetimes of all devices were plotted in an Arrhenius plot shown in Fig. 4. If we fit the data points with a straight line, we obtain an activation energy around 1.8 eV. In the same plot we included some of the reported lifetime data for InGaP HBTs at lower temperatures and lower stress currents.[19,21] We can see that at lower stress temperatures, the activation energy is lower and the lifetime is dependent on the stress current. If we fit the data with the equation obtained above, we obtain the curves shown in the figure. The activation energy for the thermally activated process and that for the recombination enhanced process were taken to be 1.8 and 1 eV, respectively. The three curves correspond to stress current densities of 25, 11, and 5.2 $\mathrm{KA/cm^2}$, the values used for the experimental tests. Considering that the data were from different sources and the devices may have different structures and different processes, the model fitting is very good.

So, it is clear that the wafer level reliability test can only provide information on device reliability related to thermally

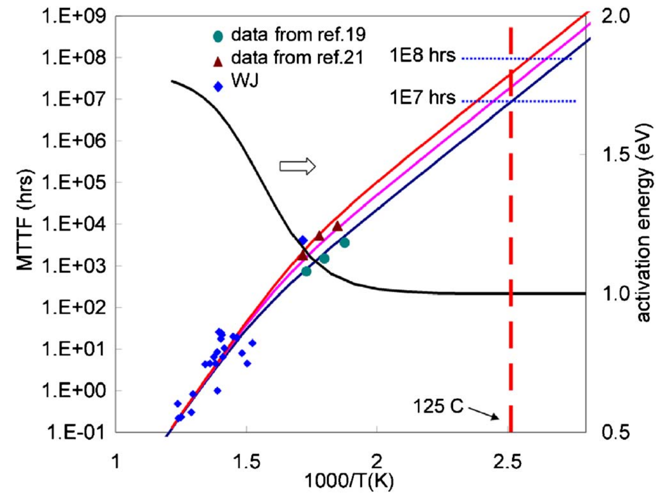

FIG. 4. (Color online) Arrhenius plot of MTTF vs $1/T$. Dots are experimental data, lines are fitted curves using our model. The current densities used are 5.2, 11, and 25 $\mathrm{KA/cm^2}$.

activated process. In order to get more accurate prediction, one has to use lower stress temperatures so that the recombination enhanced process dominates. From this figure we can reasonably expect that the MTTF of an InGaP HBT lies between 10^7 and 10^8 h at 125 °C junction temperature with commonly used collector currents.

The reason that the MTTF shown in Eq. (15) is current dependent is recombination enhanced defect generation. So what really matters is the base current or the current gain during stress. Equation (15) can be rewritten as

$$\mathrm{MTTF} \approx \frac{e^{\Delta\varepsilon/KT}}{BI_{cs}\sqrt{2\beta_0/\beta_s}}, \tag{20}$$

where β_s is the current gain at the stress condition and β_0 is that at room temperature. So, the smaller the β_s is, the smaller is the lifetime. This again agrees with experimental findings.

V. CONCLUSIONS

We have presented a phenomenological model for the lifetime prediction of GaAs based HBTs using accelerated life test. Both thermal activation process and recombination enhanced defect generation process were considered phenomenologically. At high stress temperatures, the lifetime of the transistor is determined by the thermal activation process and is independent of the stress current. But at low stress temperatures, the device's lifetime is controlled by the recombination enhanced defect generation process and is dependent on the stress current. The model has been used to fit experimental data, and very reasonable agreement was obtained. The model is valid for all stress temperatures and stress currents. It provides a good guideline for projecting lifetimes using accelerated stress test.

[1]H. Sugahara, Int. J. High Speed Electron. Syst. **5**, 381 (1994).
[2]S. R. Bahl, L. H. Camnitz, D. Houng, and M. Mierzwinski, IEEE Electron Device Lett. **17**, 446 (1996).
[3]N. Pan, J. Illiott, M. Knowles, D. P. Vu, K. Kishimoto, J. K. Twynam, H. Sato, M. T. Fresina, and G. E. Stillman, IEEE Electron Device Lett. **19**,

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115 (1998).
[4]A. Gupta, A. Young, and B. Bayraktaroglu, GaAs MANTECH Conference, 2001.
[5]H. F. Chau, B. Lin, Y. Chen, M. Kretschmar, C. P. Lee, N. L. Wang, X. Sun, W. Ma, S. Xu, and P. Hu, Digest Compound Semiconductor IC Symposium, paper J5, November 2006.
[6]H. F. Chau, C. P. Lee, C. Dunnrowicz, and B. Lin, IEEE GaAs Mantech Tech Digest, paper 3B, April 2002.
[7]M. E. Hafzi, L. H. Pawlowicz, L. T. Tran, D. K. Umemoto, D. C. Streit, A. K. Oki, M. E. Kim, and K. H. Yen, GaAs IC Symp. Tech. Digest, 1990, pp. 329–332.
[8]D. Cheskis, A. P. Young, and B. Bayraktaroglu, GaAs Reliability Workshop Proc., 2000, pp. 167–179.
[9]T. Henderson, Microelectron. Reliab. **39**, 1033 (1999).
[10]T. Henderson, Microelectron. Reliab. **36**, 1879 (1996).
[11]C. S. Whitman, Microelectron. Reliab. **46**, 1261 (2006).
[12]D. V. Lang and L. C. Kimerling, Phys. Rev. Lett. **33**, 489 (1974).
[13]H. Sumi, Phys. Rev. B **29**, 4616 (1984).
[14]S. L. Chuang, M. L. Ukita, S. Kijima, S. Taniguchi, and A. Ishibashi, Appl. Phys. Lett. **69**, 1588 (1996).
[15]H. Wang, G. I. Ng, and A. A. Hopgood, J. Phys. D **31**, 3168 (1998).
[16]M. Schubler, B. Mottet, C. Sydlo, V. Krozer, H. L. Hartnagel, and R. Jakoby, Microelectron. Reliab. **40**, 1733 (2000).
[17]R. E. Welser and P. M. DeLuca, GaAs Reliability Workshop Proc., 2001, pp. 135–157.
[18]T. Henderson, International Electron Device Meeting Tech. Digest, 1995, pp. 811–814.
[19]K. T. Feng, L. Rushing, P. Canfiled, and L. Flores, GaAs Reliability Workshop Proc., 2001, pp. 159–180.
[20]B. Surridge, J. Law, B. Oliver, W. Pakulski, H. Strackholders, M. Abou-Khalil, and G. Bonneville, GaAs MANTECH Conference, 2002.
[21]T. Henderson, J. Hitt, and K. Campman, IEEE Compound Semiconductor IC Symposium Digest, 2004, pp. 67–70.

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