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DC Conduction and Low-Frequency Noise Characteristics of GaAlAs/GaAs Single Heterojunction Bipolar Transistors at Room Temperature and Low Temperatures

V. K. Raman, C. R. Viswanathan, and Michael E. Kim

***Abstract* —The dc conduction and low-frequency noise characteristics of GaAlAs/GaAs single heterojunction bipolar transistors (HBT's) have been investigated at room temperature and at temperatures down to 5 K. The I_c dependence of the current gain has been investigated at various temperatures. The low-frequency noise characteristics exhibit both $1/f$ and generation–recombination (g–r) components. The noise characteristics are sensitive to changes in base current and insensitive to changes in V_{ce}, thus suggesting that the noise source is located in the vicinity of the emitter–base heterojunction. The noise spectrum follows a simple model based on minority carrier trapping effects at the heterointerface.**

I. Introduction

The GaAlAs/GaAs heterojunction bipolar transistor is gaining considerable interest as an excellent low $1/f$ noise device for analog/microwave, digital, and A/D conversion applications [1], [2]. Since the carriers are injected from a wider band gap GaAlAs emitter to a narrow band gap GaAs base, one can engineer the doping in the emitter region such that a lightly doped region occurs near the emitter–base junction while the rest of the emitter is heavily doped for contact purposes. The base region too can be heavily doped without affecting the injection efficiency. This results in a considerable reduction in emitter–base junction capacitance and base series resistance and hence a remarkable improvement in speed. With a heavy base doping, phenomena such as emitter crowding, base width modulation, and punch-through effects are also minimized, resulting in better performance of the device. Since there are problems associated with realizing collector–base heterojunctions with good electrical characteristics, the single HBT's are emerging as devices much superior to DHBT's. Though the high-frequency noise has been investigated in detail by several authors, the low-frequency noise behavior of these technologically important devices has been studied much less. The low-frequency noise is a key parameter of interest from the point of view of reliability, phase noise, and an understanding of the effects of trapping on device performance [3], [4].

No unified theory exists for low-frequency ($1/f$) noise behavior, even for conventional homojunction bipolar transistors (BJT's), although experimental evidence suggests that defects and surface states at the emitter–base junction are responsible for the noise [5]. A mobility fluctuation model based on Hooge's hypothesis [6] has also been proposed [7] and contradicted by several results [8]. A simple method of implementing the natural feedback action of actively biased devices has been utilized to locate the low-frequency noise generator in bipolar transistors [9], [10]. The results published so far indicate that there is no clear understanding of the exact physical origin of the noise for the conventional BJT's. The situation is worse for the complex HBT's. Blasquez *et al.* [11] have studied the current noise in GaAlAs/GaAs HBT's and reported that the devices displayed a small $1/f$ noise at low frequencies and a fairly high level of recombination noise at intermediate and high frequencies. Low-frequency noise measured in high-current-gain GaAs/GaAlAs DHBT's has been shown [3] to originate from the base and is found to be interface $1/f$ and generation–recombination (g–r) noise. All these measurements have been done at room temperature. There are certain unique advantages in operating these devices at lower temperatures, such as mobility enhancement and hence higher speed. Thus it is extremely important to understand the conduction properties and the low-frequency noise behavior at lower temperatures for cryoelectronic applications. In this paper we report the dc conduction and low-frequency noise characteristics of GaAlAs/GaAs SHBT's at room temperature and at temperatures down to 5 K. The devices exhibit stable characteristics at low temperatures and the offset voltage is slightly reduced at lower temperatures. The low-frequency noise spectra exhibit both $1/f$ and g–r components and the presence of g–r components is possibly due to distributed traps at the heterointerface. The noise spectra follow a model based on minority carrier trapping effects at the heterointerface.

Manuscript received August 20, 1990; revised January 17, 1991. This work was supported by TRW and by the state of California through the 1988–89 MICRO Program.
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IEEE Log Number 9144267.

II. Experimental

The cross section of a typical HBT structure, illustrated schematically in Fig. 1, is part of an integrated circuit process [2]. The main feature of the structure is the self-aligned base

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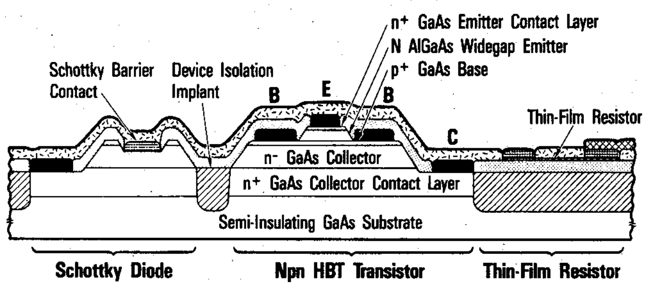

Fig. 1. Schematic cross section of the HBT device.

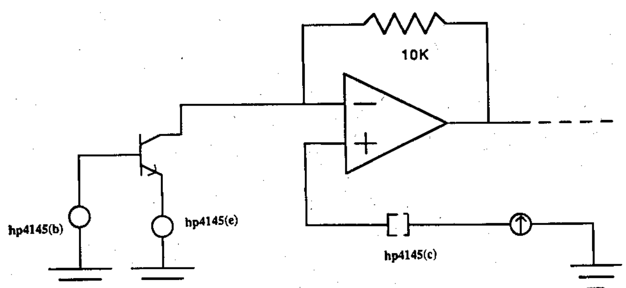

Fig. 2. Connection configuration for noise measurements. The device is connected in the common-emitter mode.

ohmic metal to reduce the parasitic external base resistance. The device isolation has been achieved by the boron implant region, and the semi-insulating GaAs substrate provides a natural radiation hardness. The devices typically have 3×10 μm^2 emitter sizes and the layers are grown by molecular beam epitaxy (MBE). The structure consists of a semi-insulating GaAS substrate of 25 mil thickness, a 0.6 μm n^+ collector contact and buffer layer, a 0.7 μm n^- collector layer, a 0.15 μm p^+ base layer, and a 0.12 μm n wide-gap GaAlAs emitter layer. The emitter was separated from the base by a graded layer with aluminum composition varying from 0.3 to 0 to reduce the band spike and velocity overshoot effects.

The $I_c - V_{ce}$ characteristics were measured using an HP 4145B parametric analyzer. Low-frequency noise was measured in an automated system whose details have been described elsewhere [12]. The system consists of a three-stage low-noise amplifier, and an HP 3561A spectrum analyzer was used to record the spectral density of the noise. The entire system was controlled by an IBM personal computer; each data point was averaged over 200 times and the signal was normalized to a 1 Hz resolution bandwidth. The biasing current and voltages were derived from the HP 4145B parametric analyzer itself. The collector current was fed to the input of the first stage of the amplifier as shown in Fig. 2. In this way, the V_{ce} and I_b values can be independently monitored during noise measurements. The fluctuations in collector current were thus measured as output noise. Low-temperature measurements were done using a 68 pin liquid helium dewar from R. G. Hansen Associates. The temperature was controlled with a Lakeshore DRC 82C temperature controller. Measurements were typically done on batches of five samples, and the results were fairly reproducible.

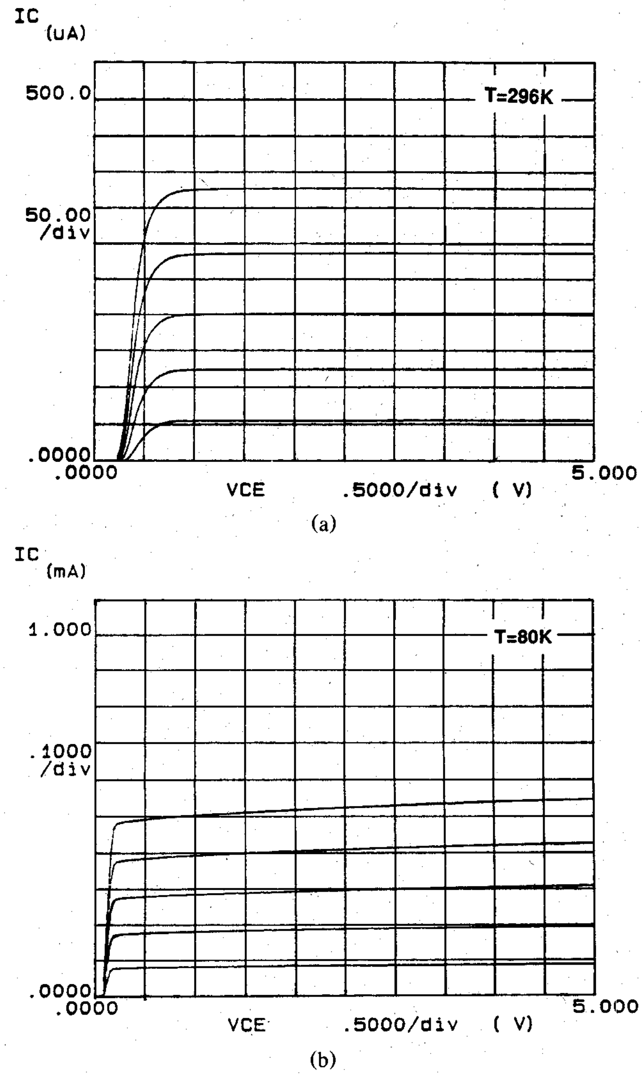

Fig. 3. Common-emitter $I_c - V_{ce}$ characteristics at (a) 296 K and (b) 80 K. The base current starts from 1 μA and increases in steps of 1 μA.

III. Results and Discussion

A. dc Characteristics

Parts (a) and (b) of Fig. 3 show typical $I_c - V_{ce}$ characteristics measured at 296 K and 80 K. No marked transient or kink effects were observed at any temperature. However, the characteristics show a finite offset voltage (of the order of 0.3 V at room temperature) in the saturation region. This offset voltage normally arises from the dissimilarity between the emitter–base heterojunction and the base–collector homojunction and such associated asymmetry effects [2] as the different turn-on voltages of the heterojunctions and homojunctions, the different junction areas, and the excess recombination currents in the collector space charge region. The resistive voltage drops between the base ohmic contact and the device can also contribute to this offset voltage. It is interesting to note that the offset voltage is slightly reduced at lower temperatures (typically 0.2 V at 80 K), suggesting that there is an effective reduction of the asymmetry effects. The collector space charge recombination current and the voltage drop at the base ohmic contact can also be reduced at lower temperatures, which in turn could result in an effective reduction of the offset voltage. Fig. 4 shows the gummel plots of

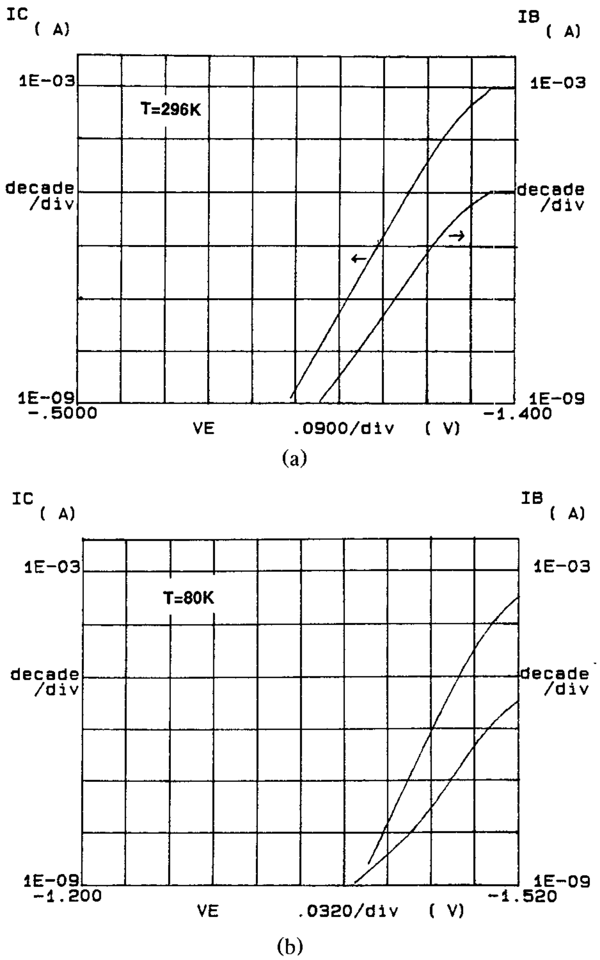

Fig. 4. Typical Gummel plots at (a) 296 K and (b) 80 K.

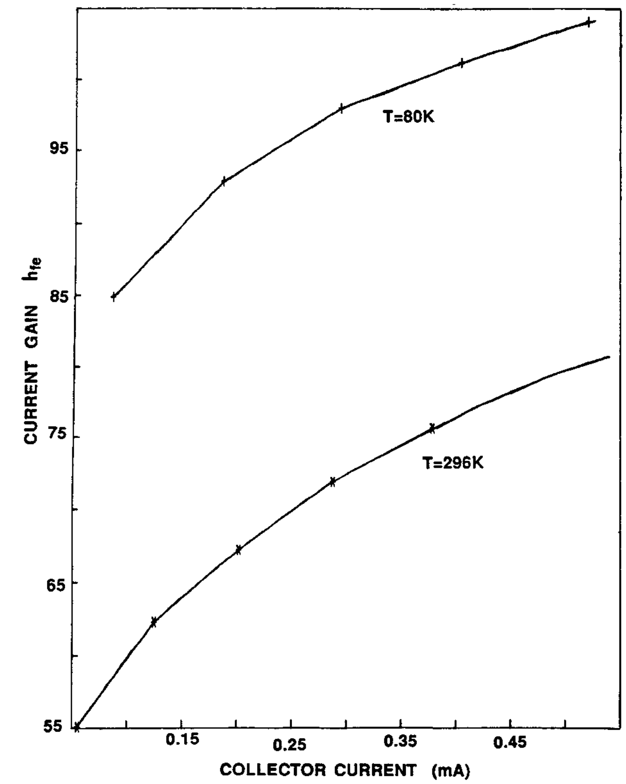

Fig. 5. Plot of h_{fe} as a function of I_c at 296 K and 80 K. $V_{ce} = 2$ V.

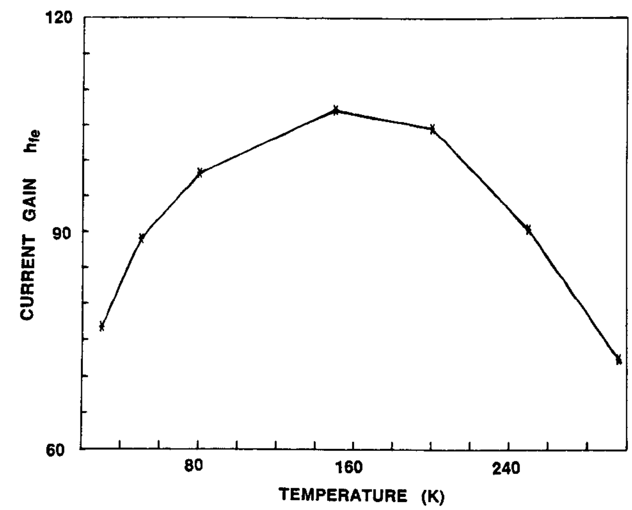

Fig. 6. Plot of h_{fe} as a function of temperature for $I_c = 0.3$ mA.

the HBT devices at 296 and 80 K. At room temperature the ideality factor for I_c is 1.1 and for I_B is 1.3. At 80 K, the corresponding values are 1.3 and 1.8. The nonideal components for I_b could be due to the heterointerface and the associated trapping effects. The exact reason for the nonideal behavior for I_c at 80 K is not known.

Fig. 5 gives the plot of the dc current gain h_{fe} $(=I_c/I_b)$ as a function of I_c for 296 K and 80 K. The fractional change in h_{fe} with decreasing I_c occurs less rapidly as the temperature is reduced. The is to be expected since the depletion region recombination current decreases with a decrease in temperature. In Fig. 6 is plotted the dc current gain as a function of temperature. The falloff in h_{fe} at higher temperatures as seen in Fig. 6 is more pronounced in these devices than in conventional silicon BJTs for the same collector current densities owing to the high density of interfacial states at the heterojunction.

B. Noise Model

Our experimental results, which will be discussed in the following section, suggest that the low-frequency noise in the HBT devices is associated with the emitter–base junction. In this subsection we describe a model for the noise behavior based on minority carrier trapping effects [14] at the heterojunction. The present devices under investigation are npn structures; hence the traps located at the interface modulate the injected electrons, giving rise to fluctuations in the emitter current I_e (and hence the collector current I_c) resulting in noise. Let us assume that the traps are simple Shockley–Read–Hall centers with concentration N_T, capture rate $C_n(=\sigma_n \nu_{\rm th})$, and energy level E_T. The trapping noise is Lorentzian with a time constant

$$\tau = C_n(n + n_1) \tag{1}$$

where $n_1 = n_t \exp\{-(E_t - E_t)/kT\}$. Here $n(x)$ is a decreasing function of x of the form (for a graded junction)

$$n(x) = n(0)\left[1 - \frac{x}{W_B}\right] \tag{2}$$

where W_B is the base width. The spectral density of the fluctuat-

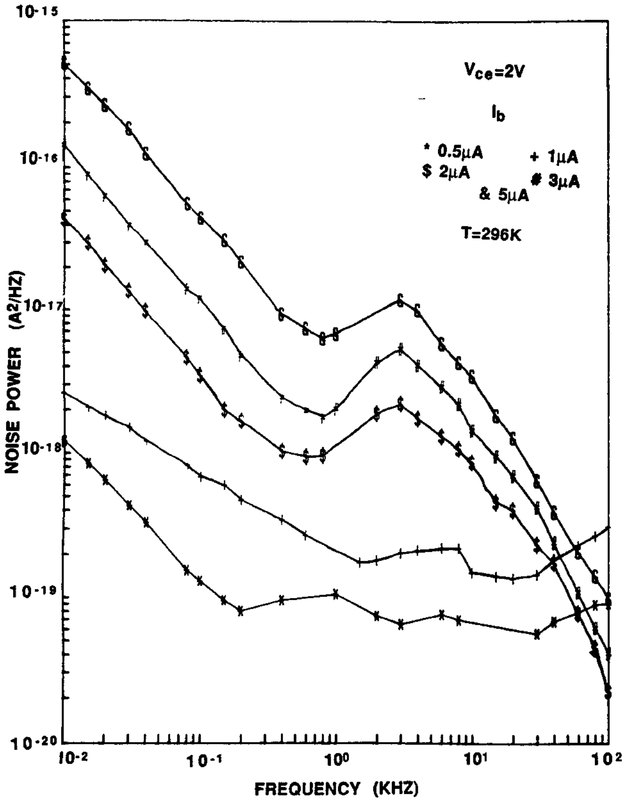

Fig. 7. Typical low-frequency noise spectra at 296 K for a fixed V_{ce} and different base currents.

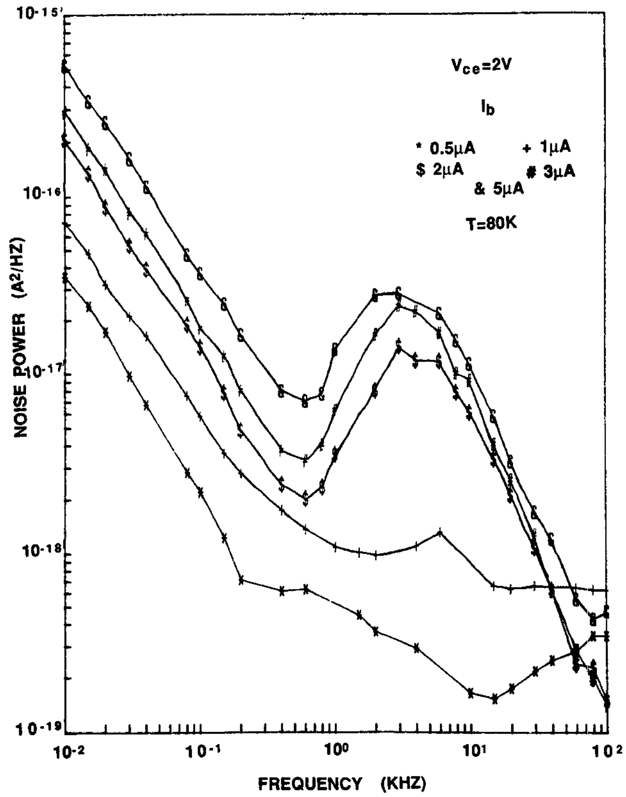

Fig. 8. Low-frequency noise spectra at 80 K.

ing carriers, N, is given by

$$S_N = A_E \int_0^{W_B} 4 N_T f_T (1 - f_T) \frac{\tau}{1 + \frac{\omega^2}{\tau^2}} dx \tag{3}$$

where A_E is the emitter area and $f_T = n_1/(n + n_1)$. Thus for a single trap the above turns out to be

$$S_I(f) = \frac{q D_n (I_E)^2}{(N_B W_B)^2 f} N_T n_1. \tag{4}$$

Therefore the output referred noise in A^2/Hz is of the $1/f$ type and is proportional to the square of the emitter current. For a distribution of traps in energy the term $N_T n_1$ is replaced by $\Sigma_i N_T n_i$. Equation (3) gives a general Lorentzian expression for the fluctuation of the carriers, whereas (4) describes the explicit dependence on the frequency for a given type of distribution of traps. Thus $S_I(f)$ represents one specific case of the more generalized spectral density, namely S_N.

C. Experimental Results on Noise Characteristics

In Fig. 7, we have shown the room-temperature (296 K) noise spectra for a fixed V_{ce} (= 2 V) and different base currents (I_b). As can be seen, the noise characteristics vary considerably as the base current changes. On the other hand, no marked change was observed in the characteristics when V_{ce} was changed. The fact that the low-frequency noise is more sensitive to changes in base current and fairly insensitive to changes in V_{ce} suggests that the noise source is located close to the emitter–base junction. This is true since any change in V_{ce} should affect the space charge region traps at the base–collector junction and the associated fluctuations at the interface. The low-frequency noise arises mainly from fluctuations in the occupancy of the traps. For $I_b = 0.5$ μA and 1 μA the noise is close to the $1/f$ type at low frequencies and becomes white noise (flat region) at higher frequencies. For higher base currents, the spectrum is $1/f$ at low frequencies and of the g–r type at higher frequencies. The results thus suggest the presence of traps at the emitter–base heterointerface and their significant contribution to the low-frequency noise. Efforts to determine the exact activation energy were not very successful since the results tend to give a shallow level with an energy of 0.069 eV. This result of a shallow trap being activated at higher temperatures is surprising and can be due to several possibilities, among them degeneracy effects, low capture cross section and a distribution of traps, related overlapping effects, or a combination of all of these!

The noise characteristics at 80 K and 5 K are shown in Fig. 8 and Fig. 9 respectively. The results are similar to room-temperature spectra in the sense that the noise magnitude increases as the base current increases. For lower base currents the spectrum is of the $1/f$ type whereas at higher base currents the spectra exhibit g–r components also. The presence of the g–r components at lower temperatures thus suggest that different traps are active in different temperature regimes. It is very difficult to find the exact origin of these electrically active defects and they can be very sensitive to the growth conditions of the heterolayers. The important conclusion is that the traps present at the GaAlAs/GaAs heterointerface affect the electrical properties of the device, in particular the low-frequency noise. The noise magnitudes are relatively higher at lower temperatures than at room temperature.

In order to check the validity of the model discussed in subsection III-B, we plot in Fig. 10 the spot noise measured at

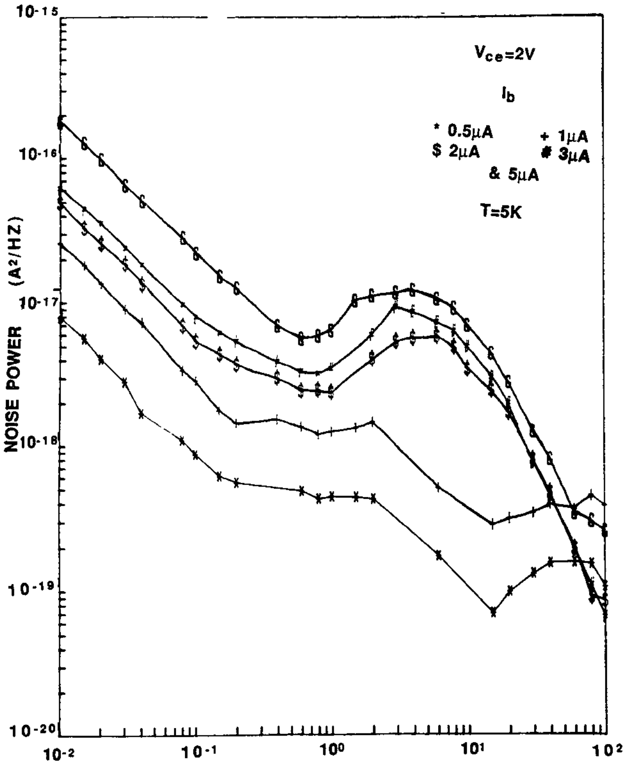

Fig. 9. Low-frequency noise spectra at 5 K.

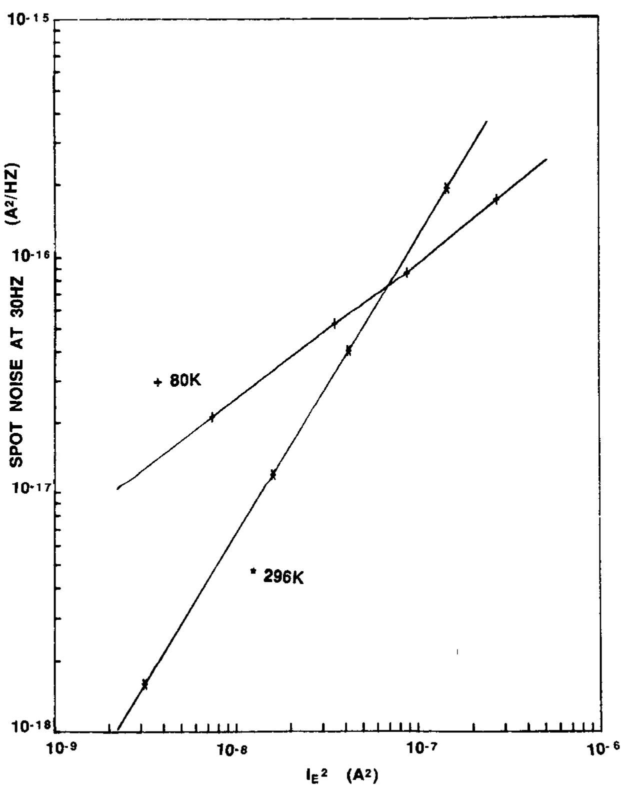

Fig. 10. Spot noise density at 30 Hz plotted as a function of I_E^2 for 296 K and 80 K. $V_{ce} = 2$ V.

30 Hz as a function of I_E^2 for 296 K and 80 K. As can be seen, the relationship is linear, as suggested by the model. However, the slope differs considerably for the two temperatures, possibly because different traps are active in the different temperature regimes (the effective $\Sigma N_T n_1$ term in (5)). Thus our results confirm that the origin of the low-frequency noise is in the vicinity of the emitter–base heterojunction and that the minority carrier trapping effects at the heterointerface are important in determining the noise mechanism in these devices.

IV. Conclusions

In this paper we have investigated the dc and low-frequency noise characteristics of GaAlAs/GaAs single HBT's at room temperature and at temperatures down to 5 K. The dc characteristics are stable at low temperatures and the current gain and the I_c dependence of the current gain have been investigated for different temperatures. The low-frequency noise characteristics vary considerably with changes in base current, thus suggesting that the possible source of noise is located close to the emitter–base junction. The noise spectrum follows a model based on minority carrier trapping effects at the heterointerface at room temperature and low temperatures.

Acknowledgment

The authors wish to thank J. Chang for helpful discussions.

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