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Analog parameters of solid source Zn diffusion $\text{In}_x\text{Ga}_{1-x}\text{As}$ nTFETs down to 10K

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Abstract
The analog parameters of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ nTFETs with solid state Zn diffused source are investigated from room temperature down to 10 K. The $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ devices are shown to yield a higher on-state current than the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ counterparts, and, consequently, a higher transconductance due to the lower bandgap. At the same time, the $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ devices present higher output conductance values. The balance between these two factors results in a higher intrinsic voltage gain ($A_V$) for $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ nTFETs at low gate bias and similar $A_V$ for both devices at high gate voltage. The transconductance is reduced at low temperature due to the increase of the bandgap, while the output conductance is decreased (improved) upon cooling, which is related to the reduction of the drain dependence of the BTBT generation rate. The temperature influence is more pronounced in the output conductance than in the transconductance, resulting in an increase of the intrinsic voltage gain at low temperatures for both devices and bias.

Keywords: TFET, low temperature, analog parameters, current conduction mechanisms

(Some figures may appear in colour only in the online journal)

Introduction
In tunnel field-effect transistors (TFET), which are essentially gated p-i-n diodes, the carrier injection mechanism is band-to-band tunneling (BTBT) [1]. TFETs are promising alternatives for low power/low voltage applications due to the fact that the BTBT mechanism can overcome the theoretical subthreshold swing (SS) limit imposed by thermal diffusion (60 mV dec$^{-1}$ at 300 K) for metal-oxide-semiconductor field-effect transistors (MOSFET) [2–4]. TFETs with a steep SS below 60 mV dec$^{-1}$ have already been experimentally demonstrated in [5].

Despite the fact that BTBT improves the switching speed of a transistor, Si-based TFETs present a very low on-state current ($I_{ON}$) due to the large and indirect bandgap of Si. The use of different source/channel materials with lower bandgap, as Si$_x$Ge$_{1-x}$ alloys [6–9] and III–V materials [10, 11], has been studied as a method for increasing $I_{ON}$.

Besides the strong potential for low power digital applications, recent studies have shown promising results for analog applications of TFETs [12–20]. The encouraging analog performance of TFETs is a result of the BTBT mechanism, which results in a very low output conductance ($g_{DS}$) when compared to the $g_{DS}$ of a MOSFET [21]. For analog applications low values of $g_{DS}$ are important because it implies in lower influence of the drain voltage, resulting in a more constant drain current independent of the output charge. The lower $g_{DS}$ for TFETs holds as long as its channel length is sufficiently long to avoid drain induced barrier thinning [22].
TFETs are typically more sensitive to defects than MOSFETs, since trap-assisted-tunneling (TAT) and Shockley-Read-Hall generation (SRH) are important current components in the off state. A study of the influence of temperature \((T)\) on TFETs enables to identify which of the conduction mechanisms is dominant \([23]\). SRH and TAT generation are thermally activated, implying that they reduce exponentially with lower \(T\), while BTBT exhibits only a small temperature influence, mainly caused by temperature-dependent bandgap narrowing. At extremely low temperatures the TAT and SRH mechanism are suppressed, making it possible to analyze separately the BTBT.

Aware of the TFETs potential for analog applications, in this work, some important analog parameters of InGaAs TFETs are investigated in order to analyze its performance, from 300 K down to 10 K, for 2 different splits, one consisting of an \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) channel, taken as the reference, and the other has an \(\text{In}_{0.7}\text{Ga}_{0.3}\text{As}\) channel, with a reduced bandgap to boost \(I_{\text{ON}}\). The analog parameters analyzed in this work are the transconductance in saturation \((g_m)\), output conductance, transistor efficiency \((g_m / I_{\text{DS}})\) and the intrinsic voltage gain \((A_V)\).

**Device characteristics**

The studied devices are \(n\)-type \(\text{In}_{x}\text{Ga}_{1-x}\) As homojunction TFETs with \(x = 0.53, 0.7\), fabricated by using Zn solid-source diffusion of the source \([25]\). The device follows the gate first approach from the University of Tokyo \([11, 24]\), and it was optimized by Alian \textit{et al} \([25]\).

Two different splits were analyzed, one device with an uniform \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) channel and the other with an extra 8 nm layer of \(\text{In}_{0.7}\text{Ga}_{0.3}\text{As}\) on top of the \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) material \([25]\). A schematic representation of the device is shown in figure 1.

The gate stack is composed of 1 nm \(\text{Al}_2\text{O}_3/3\) nm \(\text{HfO}_2\) with TiN as the metal gate. This results in an estimated equivalent oxide thickness of 1.5 nm. The drain is doped with Si \((\text{N}^{++})\) in \textit{situ} during the MBE growth, and the source is doped with Zn \((\text{P}^{++})\) using spin-on glass diffusion at 500 °C for 1 min. The transistor gate width \((W)\) and length \((L)\) are 400 \(\mu\)m and 5 \(\mu\)m, respectively.

**Analysis and discussion**

Figure 2 presents the experimental normalized drain current \((I_{\text{DS}} / W)\) and the normalized gate current \((I_{\text{GS}} / W)\), as a function of the gate voltage \((V_{\text{GS}})\) for \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) and \(\text{In}_{0.7}\text{Ga}_{0.3}\text{As}\) nTFETs, for \(V_{\text{DS}} = 1.0\) V at temperatures ranging between 300 and 10 K. The on-state current for the\(\text{In}_{0.7}\text{Ga}_{0.3}\text{As}\) device is higher than for the \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) counterpart due to the higher BTBT current for the higher In content channel. This increase is caused by the smaller bandgap, better electrostatic coupling and also can be related to higher active doping concentration \([26]\), which reduce the tunneling length.

Taking into account the effect of the temperature reduction, one can observe that, in contrast to a MOSFET where the mobility increases, all the current conduction mechanisms decrease with lower temperature, resulting in both lower \(I_{\text{ON}}\) and \(I_{\text{OFF}}\) currents in the TFETs. However, the \(I_{\text{OFF}}\) decreases relatively more than the \(I_{\text{ON}}\). This behavior can be explained by the different temperature dependence of each current conduction mechanism of the TFET. The temperature dependence is represented by the equations \((1)-(3)\), which are, respectively, the simplified current model of the, TAT and BTBT mechanism \([27-29]\).

\[
J_{\text{SRH}} \approx C_{\text{SRH}} \cdot e \left( \frac{E_F + (E_d - E_i)}{kT} \right), \quad (1)
\]

\[
J_{\text{TAT}} \approx C_{\text{TAT}} \cdot e \left( \frac{E_F + (E_d - E_i)}{kT} \right), \quad (2)
\]
where \( J \) is the current density, \( C_{1SRH} \), \( C_{1TAT} \) and \( C_{1BTBT} \) are pre-exponential constants for the simplification of the expressions, \( E_g \) is the bandgap, \( E_d \) is the defect energy level, \( E_i \) is the intrinsic energy level, \( k \) is the Boltzmann constant, \( \xi \) is the total electric field and \( C^2_{BTBT} \) is an exponential constant for the \( J_{BTBT} \) simplification.

One can immediately notice that the SRH and TAT components, which are responsible for the \( I_{OFF} \), are exponentially depending on \( T \), resulting in a high variation with the temperature. In contrast, the BTBT current, which governs \( I_{ON} \), has only an indirect influence of the temperature, which is caused by the bandgap increase at lower \( T \). This results in a smaller relative variation of the BTBT components when compared with the TAT and SRH ones.

This smaller relative variation can also be observed in the activation energy \( (E_A) \), presented in figure 3, which represents the logarithm variation of the current as a function of the inverse temperature. One can notice that for lower \( V_{GS} \), for which SRH and TAT mechanism are dominants, \( E_A \) is higher, indicating high temperature dependence. On the other hand, for high \( V_{GS} \), region where BTBT is the dominant mechanism, \( E_A \) presents low values due to its low relative temperature dependence. When comparing both different devices \( (In_{0.53}Ga_{0.47}As \text{ and } In_{0.7}Ga_{0.3}As) \) it is noticeable that the \( In_{0.7}Ga_{0.3}As \) device is less temperature dependent, i.e., presents higher BTBT component, caused by its lower tunneling length.

From figure 4 it is also possible to observe that for temperatures below 100 K the SRH and TAT components of the current are so reduced that the \( I_{OFF} \) starts to be limited by the gate current \( I_{GS} \). The dominant conduction mechanism of \( I_{GS} \) for very thin gate dielectrics is the direct tunneling across the oxide bandgap (Fowler-Nordheim), therefore, its current density can be modeled by the equation (4) [30–32]. This conduction mechanism causes lower temperature dependence of \( I_{GS} \), which is caused mainly by the bandgap variation, than in the SRH and TAT mechanisms, resulting in a limitation of the \( I_{OFF} \) by the \( I_{GS} \) at low temperatures.

\[
J_{BTBT} \simeq \frac{C_{1BTBT}}{E_g} e^{-\frac{C_{2BTBT} \xi}{E_g}},
\]

where \( J_G \) is the gate current density, \( C_{1F-N} \) and \( C_{2F-N} \) are the pre-exponential and exponential constants, respectively, for the simplification of the expressions.

Figure 4 presents the normalized \( g_m/W \) as a function of the temperature for both studied devices. The devices in figure 4(a) are biased at a drain voltage \( (V_{DS}) \) of 0.5 V, and in figure 4(b) at \( V_{DS} = 1.0 \) V. Both graphs also show data for two different gate biases, \( V_{GS} = 0.5 \) V and \( V_{GS} = 1.0 \) V. From this figure one observes that the transconductance in the

![Figure 3](image-url)  
**Figure 3.** Extracted activation energy as a function of \( V_GS \), for the \( In_{0.53}Ga_{0.47}As \text{ and } In_{0.7}Ga_{0.3}As \) devices.

![Figure 4](image-url)  
**Figure 4.** Experimental \( g_m/W \) as a function of the temperature for the \( In_{0.53}Ga_{0.47}As \text{ and } In_{0.7}Ga_{0.3}As \) devices, with \( V_{DS} = 0.5 \) V (a) and \( V_{DS} = 1.0 \) V (b).
In0.7Ga0.3As device is always higher than for the In0.53Ga0.47As channel due to its lower bandgap.

For most experimental conditions in figure 4, $g_m$ decreases with lower $T$. However, for $V_{GS} = 1.0\, V$ and $V_{DS} = 0.5\, V$ the $g_m$ in the In0.7Ga0.3As device tends to increase slightly at low temperatures. This could be related to the high series resistance (long channel device—5 $\mu$m, which decreases at low temperatures. The In0.7Ga0.3As nTFET at this bias condition has a very high current), which means that the BTBT tunnel event is very efficient, and so it is likely that the channel series resistance starts to become observable, such that the reduction of the series resistance can result in an $I_{ON}$ improvement at low $T$.

When comparing the impact of temperature for the different splits, it is noticeable that the In0.7Ga0.3As device is less influenced than the In0.53Ga0.47As counterpart. This lower temperature influence, which can also be observed in the $E_A$ curve (figure 3), is caused by the higher BTBT component in this device, owing to its lower bandgap. For higher $V_{GS}$ in both splits, where BTBT is even stronger, the same effect is noticed, resulting in a smaller temperature dependence compared to lower $V_{GS}$ values.

The transistor efficiency ($g_m/I_{DS}$) as a function of normalized $I_{DS}$ for $V_{DS} = 1.0\, V$, at temperatures ranging from 300 K down to 10 K, is presented in figure 5. For low $I_{DS}$ values $g_m/I_{DS}$ is inversely proportional to the SS, which is presented in figure 5—inset. In this region, where $g_m/I_{DS}$ exhibits its highest values, the In0.7Ga0.3As nTFET is better performing than the In0.53Ga0.47As one, due to the smaller SRH and TAT influence, which enhances the SS.

Considering high $I_{DS}$ values, the $g_m/I_{DS}$ is more dependent on the $g_m$. In this region, as the $g_m$ is higher for the In0.7Ga0.3As than for the In0.53Ga0.47As channel, it also corresponds with higher $g_m/I_{DS}$. In addition to the predominance at high currents of the BTBT, which is very weakly temperature dependent, both $g_m$ and $I_{DS}$ decrease at low temperature in the same way, resulting in a very small variation of the $g_m/I_{DS}$ with temperature.

For $V_{GS} = 0.5\, V$ the high temperature dependence can also be observed in the $I_{DS}$ as a function of $V_{DS}$ (figure 6), and as the In0.53Ga0.47As device has a higher bandgap, it is even more influenced by temperature. The plateau of this curve, i.e., the output conductance (figure 6), is also an important figure of merit in analog performance.

Figure 7 shows that for high $V_{GS}$ values ($V_{GS} = 1.0\, V$) an increase of $g_D$ is observed, which is caused by the $V_{DS}$ dependence of the effective energy window of overlap at the source–channel junction [33]. Energy window of tunneling is the energy window where the tunneling occurs, which is limited by the valence band of the source, the conduction band of the channel and the drain, and also the fermi levels of them. For high $V_{DS}$ (figure 7(b)), this effective energy window is wider than for low $V_{DS}$ (figure 7(a)), resulting in less $V_{DS}$ dependence and reaching a saturation like region.

To better understand the effect of the temperature on the $g_D$, numerical simulations were performed using Sentaurus Device simulator [34]. The simulations were performed for the uniform In0.53Ga0.47As channel device, considering the Dopant-dependent SRH, Schenk non-local TAT, non-local BTBT, and bandgap narrowing models, which parameters where obtained in [35]. Figure 8 compares the simulated and experimental $I_{DS}$ as a function of $V_{GS}$ for the In0.53Ga0.47As nTFET, showing a good match between the experimental and the simulations. Among others, the output conductance has been obtained (figure 9), where the same tendency as the experimental result ($g_D$ reduction for low temperatures) was observed.

Figure 10(a) presents the simulated energy band diagram ($E_C, E_V$) of a tilted cross section, which crosses the regions with highest BTBT generation (figures 10(b) and (c)), for three $V_{DS}$ values, at room temperature and at 100 K. From this figure one can derive that due to the slight increase of the bandgap at lower $T$, the tunneling length increase. This behavior is more clearly shown in the zoom in of this graph, shown in the inset of figure 10.
Figure 10(d) shows the BTBT generation rate at source/channel junction. One can observe from this figure that as a consequence of the small tunneling length increase at low temperature, the BTBT generation rate is reduced, which in turns results in a reduction of the BTBT current.

From figure 10(d) it is also possible to observe a reduction of the $V_{DS}$ influence on the BTBT generation rate and, consequently, the BTBT current, at low temperatures, resulting in an improvement (reduction) of $g_D$, as can be found in figure 9.

An important figure of merit for the analog characteristics of transistors is the intrinsic voltage gain, obtained by equation (5). Figure 11 presents the experimental $A_V$ as a function of the temperature for both In$_{0.53}$Ga$_{0.47}$As and In$_{0.7}$Ga$_{0.3}$As devices, with $V_{DS}$ biased at 0.5 V (figure 11(a)) and 1.0 V (figure 11(b)). It is possible to observe that for low $V_{GS}$ the In$_{0.7}$Ga$_{0.3}$As presents higher $A_V$ than the In$_{0.53}$Ga$_{0.47}$As one due to the higher influence of BTBT caused by the lower bandgap. However, for high $V_{GS}$ at low $V_{DS}$ this In$_{0.7}$Ga$_{0.3}$As device seems to suffer more from the series resistance, due to its higher current, resulting in a lower $g_m$ and $A_V$ and also more influenced by the temperature.

$$A_V = 20 \cdot \log\left(\frac{g_m}{g_D}\right).$$

(5)

The $A_V$ analysis shows that there is a competition of factors between the $g_m$ degradation and $g_D$ improvement (decrease) at low temperatures. For $V_{GS} = 1.0$ V, as $g_m$ experiences less relative influence of the temperature, the influence of the temperature on $g_D$ is the predominant factor in $A_V$, resulting in its increase for low temperatures.

For low $V_{GS}$ and at $V_{DS} = 0.5$ V, this competition of factors results in an $A_V$ almost independent on temperature, because in this bias regime the $g_m$ is more affected by the temperature due to the lower influence of BTBT. For higher
Figure 10. Simulated conduction energy and valence energy as a function of the distance of a tilted cross section (a), which cut crosses the maximum values of electron and holes BTBT generation rate (b) and (c). BTBT generation rate as a function of the cut distance for $V_{DS} = 0.4$ and 0.6 V (d).

Figure 11. Experimental $A_V$ as a function of the temperature for the In$_{0.53}$Ga$_{0.47}$As and In$_{0.7}$Ga$_{0.3}$As devices, with $V_{DS} = 0.5$ V (a) and $V_{DS} = 1.0$ V (b).
\( V_{DS} \), as the \( g_D \) is very low, a very high \( A_V \) can be observed, however, the temperature influence is even higher.

**Conclusion**

This work presents an experimental study, complemented by numerical simulations, of the analog parameters behavior of spin-on-glass Zn-diffused \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) as nTFETs down to 10 K. For In-70% the bandgap is lower, resulting in an increase of drain current and transconductance due to the BTBT dominance. However, it also presents a higher \( g_D \) than for the \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) channel. This behavior generates a competition between the influence of \( g_m \) and \( g_D \), resulting in higher \( A_V \) for \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) for low \( V_{GS} \) bias and in a similar \( A_V \) for both devices at high \( V_{GS} \) values.

In this device technology, at temperatures lower than 100 K the reduction of SRH and TAT is so pronounced that the gate current dominates \( I_{OFF} \), resulting in marginal temperature dependence below 100 K of \( I_{OFF} \). The reduction of the temperature causes a degradation of \( g_m \), however, it presents a higher BTBT component, which is less temperature dependent. The temperature influence on \( g_D \) was observed experimentally and also in the simulations and it is related to the reduction of the drain dependence of the BTBT generation rate. The temperature influence is more pronounced in \( g_D \) than in \( g_m \), resulting in an increase of \( A_V \) at low temperatures. For lower drain and gate bias (0.5 V) the \( A_V \) presents less temperature sensitivity for both devices analyzed, which could be a good option for some applications.

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