Intrinsic Gain in Self-Aligned Polysilicon Source-Gated Transistors

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Abstract

Thin-film, self-aligned source-gated transistors (SGTs) have been made in polysilicon. The very high output impedance of this type of transistor makes it suited to analog circuits. Intrinsic voltage gains of greater than one thousand have been measured at particular drain voltages. The drain voltage dependence of the gain is explained based on the device physics of the source-gated transistor and the fact that pinch-off occurs at both the source and the drain. The results obtained from these devices, which are far from optimal, suggest that, with proper design, the source-gated transistor is well suited to a wide range of analog applications.

Keywords: Source-gated transistor, polysilicon, Schottky barrier, intrinsic gain, voltage gain, TFT.

INTRODUCTION

Thin-film polysilicon layers enable large area, inexpensive devices and circuits to be made for use in systems concerned with the man-machine interface [1, 2] or cheap, disposable devices resulting from the economies of scale.

To date, the application of polysilicon devices is almost entirely restricted to digital circuits. In this paper we are concerned with analog circuits, and in particular the amplification factor or intrinsic gain of the thin-film transistor. It is difficult to obtain high intrinsic gain in conventional polysilicon FETs because the output characteristic is degraded by the so-called “kink effect” in which minority carriers generated in the high field region at the drain under saturation drift back toward the source and increase the drain current via the bipolar effect [3-5]. Therefore, output impedance is only large for small drain voltages. In a source-gated transistor, however, we have a reverse biased barrier at the source [6] that extracts any minority carriers. Furthermore, saturation is far stronger because it occurs at both the source and the drain and the output impedance can be very large.

It has been established that Source-Gated Transistors (SGTs) in polysilicon have the main characteristics that distinguish them from conventional thin-film field-effect transistors, namely a smaller saturation voltage and larger output impedance [7]. The SGTs were made by adapting a mask set used for making standard FETs using a technology based on excimer laser crystallisation of amorphous silicon. The bottom-gate structure had far from optimum performance in relation to the degradation of the transistor characteristics, due to poor passivation at the edge of the source and the large feedback capacitance formed by the large gate-drain overlap.

In this paper we examine Source-Gated Transistors made using a similar but improved technology. In particular, the gate is self-aligned with the drain contact region. The intrinsic gain is measured on various structures and is analysed in relation to the device Physics that determines the output characteristic.

TECHNOLOGY

Self-aligned source-gated transistors were made on glass substrates. Figure 1 shows a microphotograph of a typical structure. A schematic cross-section of the structure is shown in Figure 2.

Following deposition and definition of a chromium gate metal, 200nm SiN_x and 200nm SiO₂ were deposited using PECVD, followed by 40nm of a-Si:H. The amorphous silicon was dehydrogenated by baking at 450°C and various implants of BF₂ or P were used to give a range of doping levels in the polysilicon.

The drain n⁺ contacts were aligned with the gate using back exposure through the glass to define a positive resist. After chemical removal of the exposed resist regions, a high dose P implant was used to form drain contact regions aligned with the gate. The polysilicon and contact regions were formed using an excimer laser followed by definition and dry etching to form polysilicon islands. Source windows were etched in 120nm SiO₂, followed by various 5keV BF₂ or P implants in order to modify the source barrier profile. The implants were annealed at 550°C. Chromium and AlTi metal layers were deposited and defined to form a Schottky source and field plate structure shown in Figure 2. Finally, the structure was passivated using a 0.6µm nitride layer and contacts made to the source, drain and gate pads using Cr/AlTi/Cr metallisation via contact holes.

SOURCE-GATED TRANSISTOR CHARACTERISTICS

The output and transfer characteristics were measured on devices similar to that shown in Fig. 1. Despite misalignment of the source window between the two drain contacts, the current between the source and either drain was the same, in agreement with the general property of an SGT that the current is independent of source-drain separation. (d in Fig. 2). Various devices with a range of source lengths (S), source-drain separations (d) and barrier changing implants have been measured.

Examples of device characteristics are shown in Fig. 3 and Fig. 4 for two devices with different polysilicon doping levels and different barrier modifying implants. Device (b) has a higher n-type polysilicon doping and therefore requires a larger negative voltage to turn it off compared with device (a).

It is seen in Fig. 3 that the characteristics exhibit the features of an SGT namely low saturation voltage and high output impedance. [6-8]: The change of saturation voltage with gate voltage was measured to be 0.04, in good agreement with that predicted by the dielectric model of the SGT [8]. Furthermore the high output impedance is maintained right out to $V_D=20V$ with no degradation due to the “kink effect”.

While saturation in device (a) is sharp and well defined, device (b) shows a more rounded feature. This is most probably due to the high dose BF_2 implant below the Cr source and the resulting doping profile. Since the annealing temperature for this implant was limited to $550^{\circ}C$ to prevent glass compaction there will be a lot of residual damage centres and inactive boron making depletion more complicated.

Assuming barrier lowering is proportional to the electric field at the Schottky barrier interface [7], the transfer characteristic in Fig. 4 gives a barrier lowering constant of $\approx 3nm$ for

(a) and $\approx 2\text{nm}$ for (b) [8]. While the value for (a) is similar to that measured in an ideal metal-silicon Schottky diode [9], the value for (b) is much lower. The latter is probably due to a thin oxide layer in the source window and to the poor quality of the polysilicon layer following the BF_2 implant.

It has been shown previously, using computer modelling that the current crossing the source barrier is concentrated at the drain end of the source [10]. This feature is shown experimentally in Figure 5. Here we see that the drain current is insensitive to source length provided it is greater than $\approx 2\mu\text{m}$. Therefore, to maximise frequency response, the source length should be small, since a long source simply increases the source capacitance without increasing the current. For device (a) shown in Figure 3, which has a $2\mu\text{m}$ source length, the calculated f_T [11] increases to approximately 80MHz at the highest gate voltages.

INTRINSIC GAIN IN AN SGT WITH A SCHOTTKY SOURCE

The intrinsic voltage gain is given by the ratio of the transconductance g_m and the output conductance g_d . An analysis of the SGT with a Schottky barrier source shows that the transconductance is proportional to the average source current density J_s and the capacitance per unit area of the gate insulator [11]. Therefore g_m will increase with decreasing source barrier height and gate insulator thickness.

In an FET the output conductance in saturation is determined by channel length shortening with increasing V_D , combined with the effect of carrier generation in the high-field pinch-off region at the drain (the so-called “kink effect”). In the SGT we expect both these physical mechanisms to play a role but the saturation is more complicated because as V_D increases, pinch-off and current saturation first occurs under the source, as shown

schematically in Figure 6(a) and then, at higher V_D , the device also pinches off at the drain end of the parasitic FET (Figure 6(b)).

The change of drain current with drain voltage is shown schematically in Figure 7 for two gate voltages. As V_D increases from 0V, for a given gate voltage V_{G1} , the depletion layer of the reverse biased source barrier becomes thicker and the electric field under the source increases until the carriers induced by the gate are depleted. This is region (1) in Figure 7. The current at V_{SAT1} saturates because further increase in V_D does not affect the electric field under the source barrier. A further increase in V_D causes the depletion envelope to spread sideways towards the drain. In this region, (2) in Figure 7, the output conductance depends on the quality of the passivation at the edge of the source (point A in Figure 6) and its ability to minimise any rise in the normal component of the electric field under the barrier as the drain field increases. In region (2) there will be a small potential drop across the parasitic FET so the change of potential of its floating source (point B in Figure 6) will be similar to the change of V_D . However, as the floating source potential becomes more positive, the FET begins to turn off, its conductance starts to decrease and it drops more potential. Therefore, in region (2) of Figure 7 we expect a decrease in the conductance as V_D increases because the change in electric field with V_D is more uniformly spread between source and drain. Finally, when $V_D = V_G - V_T$ the parasitic FET pinches off close to the drain contact and the current in the parasitic FET saturates (V_{SAT2} in Figure 7). In this region we expect the overall conductance of the SGT to be affected by the conductance of the FET in saturation, which is dependent on channel shortening effects. Therefore, around V_{SAT2} the conductance should be influenced by the source-drain separation and the length of the channel. With both source and drain ends pinched off, a very large output impedance is expected, (region 3) which is indeed a feature of the source-gated transistor. Above $V_D = V_{SAT2}$ further increases in V_D will be dropped across

the pinch-off region at the drain and the field will increase strongly causing carrier generation via hot carriers and a rise in the output conductance (region (4) in Figure 7).

Also shown in Figure 7 is a schematic of the I_D vs. V_D curve for a higher V_G . I_D is higher so we expect a larger g_m . The change in V_{SAT1} is small because dV_{SAT1}/dV_G is small [7] but there is a shift in V_{SAT2} because of the change in $V_G - V_T$, and $\Delta V_{SAT2} = V_{G2} - V_{G1}$. Furthermore, a larger V_G will increase the electric field, particularly near the drain and an increase in carrier generation at $V_D > V_{SAT2}$ is expected. It should be noted, however, that whilst in an FET minority carrier current tends to be amplified because the source junction becomes forward biased and there is a bipolar effect (the kink effect), in the SGT the source is reverse biased, minority carriers are extracted and no amplification occurs.

INTRINSIC GAIN MEASUREMENTS

Intrinsic voltage gain (g_m/g_d) measurements were made on transistors having a range of source lengths and source-drain separations. There were also variations in the characteristic of the Schottky source barrier due to implantation of dopants below the source barrier. In general, the transconductance of the devices was poor in comparison to an equivalent FET because firstly the barrier lowering constant was low, presumably due to a thin oxide layer in the source window, and secondly the insulator was thick (200nm SiO_2 + 200nm SiN_x) compared to that in a typical polysilicon FET. This means that J_s and C_i were much smaller than optimum. The output conductance, however, was very low for certain values of V_D and strongly V_D dependent. This led to voltage gains higher than a thousand in some devices.

An example of the drain voltage dependence of the intrinsic gain in these polysilicon SGT's is shown in Figure 8 for two different gate voltages. The output characteristics were

similar to those shown in Fig. 3(b). The source-drain separations in 8(a) and 8(b) were 4 and 10 microns, respectively. To modify the barrier, a BF2 implant was made in the source window. This implant should also aid passivation, since the polysilicon region around the edge of the window will be less n-type. We see from Figure 8 that for a given V_G there are large variations in the gain with drain voltage. Since g_m does not change very much, these variations are due to changes in g_d .

With reference to Figure 8 (a), at $V_G = -36V$ the gain increases rapidly as V_D increases to V_{SAT1} , ((1) Fig. 7) which is approximately 1.5V. It then increases further as the device saturates at V_{SAT2} , ((2) Fig. 7) which since $V_T \approx -40V$, should be around 4V. The highest gain occurs when $V_D > V_{SAT2}$, ((3) Fig. 7) but as V_D becomes much larger than V_{SAT2} , the gain falls off, presumably due to an increase in g_d , as suggested above ((4) Fig. 7). Increasing V_G to -30V shows a rise in gain at low voltages, consistent with an increase in I_D and g_m . However, there is a shift in the position of the maximum gain, which is consistent with a shift of 6V in V_{SAT2} . Interestingly, the increase in gain around V_{SAT1} due to a larger g_m is very similar to that around V_{SAT2} (≈ 4). We see, therefore, that these gain curves are consistent with the general description of what is expected from the output characteristics.

Measurements on an identical structure but with a larger source-drain separation are shown in Figure 8(b). The gains at low drain voltages are similar to those in Figure 8(a) but at higher V_D maximum gains are much higher. For $V_G = -36V$, for example, measurements in Fig 8 (a) show a maximum gain of ≈ 250 for $V_D \approx 8V$. In Figure 8(b) the gain continues to rise to a value of ≈ 500 at $V_D \approx 10V$. We attribute this to a reduction of channel-shortening effects and g_d in the device with a larger source-drain separation. At $V_G = -30V$, maximum gains can be extremely large, as output conductance tends to zero. In fact, we have measured negative resistance in some devices, due to the interaction between the two high-impedance regions at

the source and drain ends of the device. Above $V_D=15V$, these measurements become very noisy and unreliable. However, if we scale the increase in gain with that measured around V_{SAT1} , the maximum gain is ≈ 5000 . It remains to be seen if these very high gains are practically useful.

A device with very different gain characteristics is shown in Figure 9. This device had a phosphorus implant in the source window which made the polysilicon more n-type. The edge passivation was therefore likely to be worse than in the previous sample. This device, which had a current ten times higher than those shown in Figure 8, did not show large variations in gain with V_G . We believe that this is due to the poor passivation and to the formation of a high field region at the edge of the source window (region A in Figure 6). Such a region could provide a situation in which the conductance is proportional to the current either due to carrier generation or due to the effect of the lateral electric field on the low peripheral barrier. Such an effect, of course, would tend to negate any increase in gain arising from an increase in current and g_m . Despite the degradation of g_d , however, gains over 500 are observed.

CONCLUSION

Self-aligned Source-Gated Transistors have been fabricated in polysilicon. Using Cr Schottky source barriers, the characteristic features of Source-Gated Transistors, namely high output impedance and low saturation voltage, were observed with an absence of the deleterious “kink effect” found in polysilicon FETs. The effective barrier lowering constant was similar to that expected in the high current devices, but many samples had low values, presumably due to the presence of a thin oxide in the source window and residual disorder

following the barrier modification implant. The calculated f_T of the highest current devices was well above 50MHz.

The drain voltage dependence of the intrinsic voltage gain (g_m/g_d) was complicated by the fact that the device first pinches off at the source and then at the drain, as drain voltage was increased. This led to a double peak in the gain characteristic with the highest gain achieved when both source and drain were pinched off. Intrinsic voltage gain in excess of a thousand was obtained in some cases. It is shown that the variations of gain with drain voltage in a well passivated structure agree well with our understanding of how the device works. The high gains were obtained by engineering very high output impedances and are well suited to analog applications. These devices were far from optimum, however, particularly in relation to g_m and their speed of operation.

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FIGURE CAPTIONS

Figure 1. Microphotograph of a self-aligned SGT in polysilicon on glass. Despite the misalignment of the source contact window and source metallisation, the current to each of the drains is the same. $W=50\mu\text{m}$, $S=2\mu\text{m}$, $d=4\mu\text{m}$.

Figure 2. Schematic cross-section of a self-aligned SGT.

Figure 3. Output characteristic of typical polysilicon SGTs showing low saturation voltage and high impedance in saturation. The n-type doping in the polysilicon layer was $1.5 \cdot 10^{12}$ and $2.5 \cdot 10^{12}/\text{cm}^2$ and the barrier modification implant was $1 \cdot 10^{13}$ and $7.5 \cdot 10^{13}/\text{cm}^2$, 5keV BF_2 for (a) and (b) respectively. $W=50\mu\text{m}$, $S=2\mu\text{m}$, $d=4\mu\text{m}$.

Figure 4. Transfer characteristics of the transistors shown in Figure 3.

Figure 5. Dependence of drain current on source length. Most of the current flows at the edge of the source opposite the drain. $W=50\mu\text{m}$, $d=6\mu\text{m}$.

Figure 6. Schematic showing the two pinch-off states of the SGT. In (a) the semiconductor is pinched-off at the source. In (b) when $V_D=V_G-V_T$ the semiconductor pinches off at both the source and the drain. A is the corner of the source most sensitive to drain field. B is the position of the floating source of the parasitic FET.

Figure 7. Schematic showing how the drain current changes with drain voltage for two values of V_G based on our understanding of how the SGT works.

Figure 8. Intrinsic gain measurements on two identical devices apart from the source drain separation. $W=50\mu\text{m}$, $S=2\mu\text{m}$, $V_T \approx -40\text{V}$.

Figure 9. Intrinsic gain measurements on a high-current device with poor edge passivation.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

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