Analysis of a Substrate Leakage Current at MMIC

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Abstract— **This paper describes characteristics of a substrate leakage current flowing to the substrate in millimeter wave CMOS IC. The effects of the substrate current are investigated according to operating modes of a Power Amplifier (PA) – Class-A and Class-B. Due to the characteristics of V and I at the drain, better performance could be expected in the operation of Class-B.**

I. INTRODUCTION AND BACKGROUND

First of all, use of a CMOS process has several advantages to meet market requirements. But at millimeter wave, designers using a CMOS process meet two challenges- low substrate resistivity and low power gain.

An unwanted current flowing to body by low substrate resistivity reduces the current gain of an overall system. This reduction is critical to a system because a CMOS device has low power gain at millimeter wave. Especially operating in Class-A gives a worse effect to the current gain because TR's of Class-A are always in turn-on region. We should have attention to this point since most of present millimeter wave PAs operate in Class-A.

In most cases, designers use a triple-well to suppress such a substrate leakage current. But the using of a triple-well makes a CMOS process cost higher, then the attractiveness of a CMOS process compared with other compound semiconductor processes is diminished.

II. RESULTS

A current flowing to the substrate is caused by two breakdown mechanisms – a Zener breakdown and an avalanche breakdown. The Zener breakdown is a dominant cause of the current flowing to a substrate when drain-source voltage(V_{ds}) is below 5V. The Zener breakdown occurs due to elect-hole pairs generated by electric field in the substrate. In 2.5V TR of 60nm CMOS process, the leakage current by this breakdown starts around 2.5V of V_{ds} and is directly proportional to a magnitude of a source current (not drain current). On the other hand, body-source voltage (V_{bs}) is a less dominant factor to the substrate current than V_{ds}. The current has a weakly decreasing tendency when V_{bs} is decreasing when V_{bs} is below a threshold voltage. That is, the V_{ds} and the source current could be considered main factors to determine the substrate current.

Fig 1. shows a body current curve due to V_{ds} at V_{bs}=0 and various gate-source voltage(V_{gs}) values. When source current is 860mA at V_{ds}=2.5V in 2.5V-TR of 60nm CMOS process, a current of 3mA flows to the body at V_{ds}=2.5V and a current of 81mA flows at V_{ds}=3.5V. We see that the body current abruptly increases proportionally to a square of the increment of V_{ds}.

Avalanche breakdown - another cause of breakdown current - is a dominant factor when V_{ds} is beyond 5V. But a practical TR doesn't reach this breakdown region due to a limitation of V_{gd} breakdown.

The problem of such a substrate current is that it reduces a current gain of an overall system. Under a quasi-static assumption, the substrate current is sum of a current caused by the breakdown and a current through parasitic impedances. The unexpected additional current by the breakdown reduces current swing. Especially, such reduction of current gain is critical to MMIC design in which a TR has a low power gain.

A Class-A shows most serious reduction of current gain among the linear PAs. In a case of Class-A, a TR remains a turn-on state when V_{ds} is beyond 2.5V. So the leakage current occurs. Such a substrate leakage current flows in the direction of reduction of a current swing at drain and the current gain is diminished significantly. Further, because the substrate current is proportional to the square of an overdrive voltage, the leakage current flowing to a substrate strongly saturate the output power around the compression point.

A Class-B stands against reduction of current gain by a leakage current. Because the TR resides in a cut-off region unlike a Class-A when V_{ds} is beyond 2.5V, operating in Class-B suppresses leakage current flowing to the substrate. As a result, the reduction of current gain is minimized because only a current through the parasitic impedance reduces the gain.

The leakage current flowing to substrate is one of the most important factors to saturate an output power of a PA. When the input power level is low, the output power increases linearly as input power increases gradually. But because the leakage current starts to flow and increase from the point at V_{ds}=2.5V, the leakage current blunts the increase of output power. So an operating PA in Class-B has an advantage to generate high output power that it reduces the leakage current by turn-off of a TR when the V_{ds} is maximized.

Further, such a leakage current degrades efficiency of an overall system. Because the current at drain is sum of the source current driven by V_{gs} and the leakage current, the leakage current increases the DC current flowing into a system. So reduction of leakage current is an important issue for efficiency.

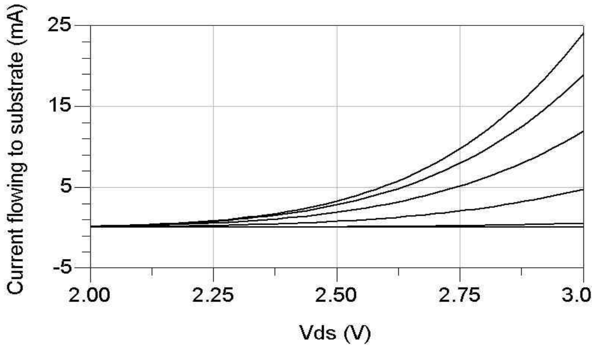

Fig. 1. A body current curve due to V_{ds} at V_{bs}=0 at various V_{gs}

III. SIMULATION

An introduction of a cascode structure is very useful when a PA is designed at millimeter-wave. It reduces the Miller effect by separation of an input node and an output node. Due to higher isolation in a TR, the stability of a system is improved dramatically. In the view of breakdown voltage of a TR, usable supply voltage and power capacity are increased twice and the efficiency of matching network is improved owe to reduction of turn ratio.

Fig 2. shows a source, a drain and a body current of a common gate TR in such a cascode PA operating in Class-A. In a cascode structure, the maximum degradation leakage current flows in the common gate TR because the maximum voltage swing occurs at the drain of this TR - maximum V_{ds} occurs. So, a reduction of output current swing happens.

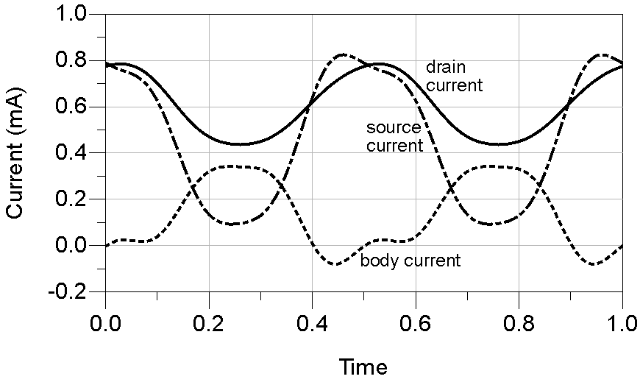

Fig. 2. A body, a source and a drain current in Class-A

Fig 3. shows same kinds of currents using triple-well in a common gate TR. In this case, the leakage current is added to the source current, then the current swing driven by common source TR appears at the output node with the same magnitude.

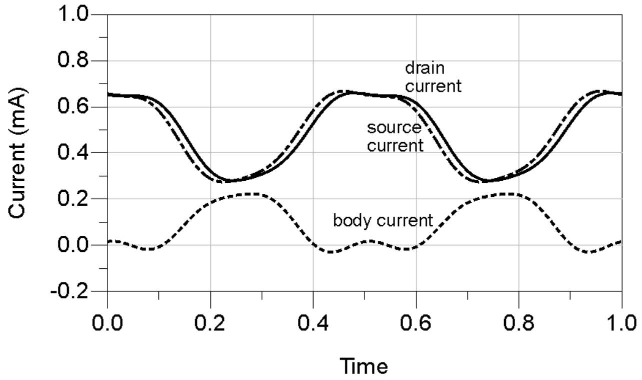

Fig. 3. A body, a source and a drain current in Class-A with a triple-well common gate TR

Fig 4. shows a source, a drain and a body current of a common gate TR operating in Class-B. When the maximum V_{ds} occurs, the common gate TR is in turn-off condition. So the current flowing to the substrate is suppressed. As a result, the current swing driven by common source TR appears at the output node with only a little reduction similarly to a triple-well case.

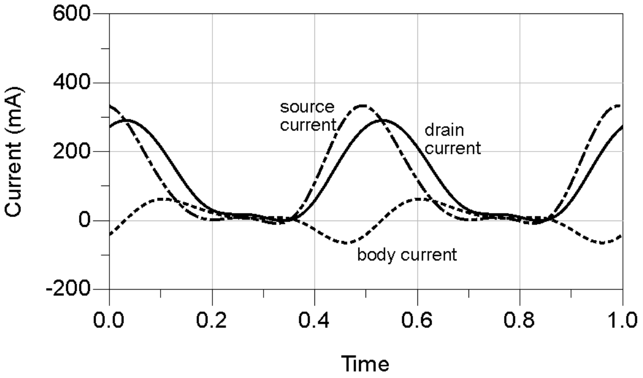

Fig. 4. A body, a source and a drain current in Class-B

IV. CONCLUSION

We presented characteristics of a leakage current and show that a Class-B or a Class-AB are suitable to a MMIC PA due to its inherent merit of reducing leakage current. As a result, when a PA is designed at millimeter wave, consideration of the effects of a leakage current is very important in order to obtain a higher power gain, higher output power and higher efficiency.

ACKNOWLEDGEMENT

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