Analysis of Active Matrix GaN-Based HFET Switch Circuits Integrated With GaN LED Micro-Displays

Ghien An Shih and Jian Jang Huang, *Member, IEEE*

Abstract—We demonstrate a novel GaN-based heterojunction field effect transistor (HFET) active-matrix circuit for an light-emitting diode (LED) microdisplay. Simulation results are shown with basic and improved circuits. Variations of process and material growth conditions are discussed by correlating device parameters with LED flow currents in this circuit. It shows that the HFET-LED control circuit approach provides a stability path to mitigate variations of LED currents during operations.

Index Terms—GaN, heterojunction field effect transistor (HFET), light-emitting diode (LED), microdisplays.

I. INTRODUCTION

WHITE-LIGHT light-emitting diodes (LEDs) have, recently, become an emerging technology for general lighting [1]. The LED arrays can also be used as microdisplays, which have the applications for projection displays, impaired eye cornea replacements, etc. T[2]–[4]. To lighten up an LED pixel in an array, passive matrix addressing method is generally employed [5]. Rows are selected one by one with a current imposed to each pixel of that row to obtain the desired brightness. The main disadvantage of the passive matrix addressing is that a high current is needed to achieve high peak luminance. And such a high current is one of the limiting factors of pixel lifetimes and also numbers of rows and columns in a microdisplay. Furthermore, the nonuniformity of pixel brightness caused by the variations of turn-on voltages of LEDs is also a disadvantage of this passive-matrix addressing method. Therefore, a new pixel driving scheme is necessary to improve power efficiency and device uniformity of an LED microdisplay.

To apply LED arrays to microdisplays, we propose a novel active heterojunction field-effect transistor (HFET)-LED approach which is similar to thin film transistor-liquid crystal display (TFT-LCD). In this approach, GaN-based HFETs are embodied monolithically with GaN-based blue LEDs. Both HFET switches and LEDs share the same substrate (either SiC or sapphire) so that pixels of the blue LED array can be separately controlled by HFET switches. The active matrix approach has the advantage of less power consumption on the conducting metal strips and thus higher power efficiency since only the selected pixel is on. We believe this is the first time an active LED matrix addressing approach is proposed and simulated.

Manuscript received June 20, 2005; revised August 22, 2005. This work was supported by the National Science Council of Taiwan, R.O.C. under Contract NSC 94-2215-E-002-012. The review of this letter was arranged by Editor P. Yu.

The authors are with the Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C. (e-mail: jjhuang@cc.ee.ntu.edu.tw).

Digital Object Identifier 10.1109/LED.2005.857721

In this letter, we first simulate currents flowing through LEDs at both on and off states with HFET control switches. We next propose an improved switch circuit and then discuss the LED current dependence on the LED threshold voltage ($V_{T,LED}$) and contact resistance. The variation of HFET threshold voltage ($V_{T,HFET}$) is also described. Simulation results, based on the device performance measured for an LED and an HFET, indicate that the proposed circuit has high immunity to the variation of threshold voltages of GaN-based HFETs and AlGaIn/GaN LEDs.

II. DEVICE MODELS AND SIMULATION TOOLS

The fully integrated nitride based active matrix HFET-LED microdisplays can be realized with an LED p-i-n layer structure grown on top of an HFET structure. Contact and interconnect metal pads are deposited on suitable layers after etching processes.

We use an automated integrated circuit modeling-Spice (AIM-SPICE) analog-circuit simulator to simulate the current waveforms flowing through the LED. The LED device parameters in this simulation are referred from [6] and [7] while HFET model is from [8], [9]. The series resistance of an LED is $26\ \Omega$ and its threshold voltage is about 3.45 eV. The mesa area of an HFET is around $120 \times 100\ \mu\text{m}^2$ while $300 \times 300\ \mu\text{m}^2$ for an LED. The on-state resistance and breakdown voltage of an HFET are $40\ \text{m}\Omega\cdot\text{cm}^2$ and 60 V, respectively. And the HFET leakage current in the pinchoff region under source/drain voltages of interest is approximately $0.4\ \mu\text{A}$ [10].

III. SIMULATION RESULTS AND DISCUSSIONS

A. Basic Circuit

The basic control circuit for a LED microdisplay is very similar to that for the TFT-LCD. We use an active matrix circuit shown in Fig. 1(a). The GaN-based HFET (T1) behaves as a current source controlled by the data voltage V_{data} while the HFET T2 acts as a switch transistor. The voltage across V_{GS} of T1 is stored in C1. R is the series resistance of an LED ($26\ \Omega$). When $V_{\text{select}1}$ becomes high at a certain time interval, T2 is turned on. And then the signal of V_{data} is transferred to the gate of T1. Assuming T1 is biased sufficiently to stay in saturation, the drain current is determined only by the gate-source voltage V_{GS} of T1. The LED device will be turned on when V_{data} is high and will be biased at a constant current determined by T1. Since the n-type HFET is a normally on device, the operation of HFET-LED arrays is different from that for normally off TFT operation. The gate bias voltage for the switch transistor is typically 0 V for normally off TFTs while a negative bias is applied for HFETs.

Fig. 1. (a) Basic GaN-based HFET-LED active matrix circuit for LED microdisplays. (b) An alternative circuit to suppress leakage currents at the off state. (c) Simulated LED currents [left (for circuit in (a)), right [for circuit in (b)].

In our case, $V_{select1}$ is biased at -7 V during the off-state of the pixel. The power consumption can be neglected when T2 is complete off. The result is shown in the left part of Fig. 1(c). The main problem with this simple driving scheme is the 15 mA leakage current in the off state. When V_{data} line is selected on but $V_{select1}$ line is off, T2 can not be turned off completely due to the negative threshold voltage property of the depletion mode n-HFET. Thus, the data transferred into the gate of T1 leads to unavoidable currents flowing into LEDs, causing a leakage current. In this case, some LED pixels are mistakenly on when they are supposed off. To resolve the problem, we present an alternative circuit.

B. An Alternative Circuit to Suppress the Leakage Current

As shown in Fig. 1(b), we include one more switch, T3, to control the on and off states. We use two selection lines ($V_{select1}$, $V_{select2}$) and one data line (V_{data}). When $V_{select1}$ and $V_{select2}$ lines are both high and V_{data} is low, the data signal is transferred into the gate of T1. The LED remains in the off-state until the data voltage becomes high. Although the additional T3 can limit the LED current flow, it successfully suppresses the leakage current in the off state [see the right part of Fig. 1(c)].

One of advantages of the HFET-LED switch circuits is their ability to reduce the influence of device growth and process vari-

Fig. 2. (left) LED current with a normal LED threshold voltage ($V_{T,LED} = 3.45$ V). (right, dashed line, -13.06% change) LED currents with $110\% V_{T,LED}$ and (right, solid line, $+13.22\%$ change) with $90\% V_{T,LED}$.

ations on the LED currents. For example, threshold voltages of LEDs across the wafer are usually nonuniform. In our switch circuit, the existing contact resistance of an LED provides a feedback path to reduce variations of LED currents. During the time the LED pixel encounters unexpected increase of currents, it creates additional voltage drops across the contact resistor. In Fig. 1(a) or (b), since the biased voltage V_{cc} is fixed, voltages across transistors (T1 and T3) are decreased. The current can thus be stabilized. In our active matrix circuit, $+10\%$ and -10% changes of the $V_{T,LED}$ of an LED result in around -13% and $+13\%$ variations of LED currents (right side of Fig. 2). In contrast, for a passive LED arrays which voltages are applied directly across LED devices, variations of $\pm 10\% V_{T,LED}$ result in around 24% changes of LED currents under the same biased voltage across LED terminals in our simulation. Therefore, the active matrix circuits have the ability of better current compensation due to the effects of feedback path from LED module to transistors T1 and T3. The 46% (from 24% to 13% variations) reduction of current variations can greatly ease the LED process control during manufacturing. Also the stability feedback circuit can relieve the impact of changes of the LED contact resistance. Only -5.92% and $+6.75\%$ changes in LED currents were found with $+20\%$ and -20% changes of contact resistance (not shown in the figures), which is compared to -16.09% and $+23.08\%$, respectively, changes of LED currents for the passive LED array with voltages applied directly across LED terminals.

Another issue that is commonly seen in the active matrix display is the variation of “switch” device performance across the wafer. Among the device parameters of an HFET, $V_{T,HFET}$ variations usually result in variations of LED currents. An intuitive way to mitigate LED current variations is to treat the contact resistor of the LED as the feedback path again. This resistor contact in the LED model provides a feedback to reduce voltage and temperature impacts on current sources. The relationship between LED currents and $V_{T,HFET}$ can be seen in the right part from Fig. 3. Currents vary from $+0.36\%$ to -0.56% when $V_{T,HFET}$ swings from -2.6 V to -1.6 V, assuming 0% change of the current at $V_{T,HFET} = -2.1$ V (the left part of Fig. 3).

Fig. 3. (left) LED current under the normal HFET threshold voltage ($V_{T,\text{HFET}} = -2.1$ V), (right, dashed line, $+0.36\%$ change) LED currents with $V_{T,\text{HFET}} = -2.6$ V and (right, solid line, -0.56% change) $V_{T,\text{HFET}} = -1.6$ V.

It shows that the HFET-LED switch circuit is relatively stable under the conditions of process variations.

IV. CONCLUSION

A novel active matrix HFET-LED control circuit for an LED microdisplay was discussed. It shows that this circuit provides a stability path to mitigate variations of LED currents during operations. Variations of LED currents are much smaller for active matrix HFET-LED arrays than those for passive LED arrays given changes of $V_{T,\text{LED}}$, and LED contact resistance. More-

over, the HFET-LED circuit is relatively stable from HFET device variations. The integration of HFET-LED device will create a new research topic to accomplish the high performance LED system, and yet at low cost.

REFERENCES

- [1] S. Muthu, F. J. P. Schuurmans, and M. D. Pashley, "Red, green, and blue LEDs for white light illumination," *IEEE Sel. Topics Quantum Electron.*, vol. 8, no. 2, p. 333, Feb. 2002.
- [2] H. W. Choi, C. Liu, E. Gu, G. McConnell, J. M. Girkin, I. M. Watson, and M. D. Dawson, "GaN microlight emitting diode arrays with monolithically integrated sapphire microlenses," *Appl. Phys. Lett.*, vol. 84, no. 13, pp. 2253–2255, Mar. 2004.
- [3] Y. R. Song, C.-S. Won, H. Ahn, D.-Y. Han, Y.-S. Choi, and S.-J. Lym, "The study on optimal design and optical properties of LED module for full-color displays," in *Proc. 5th Int. Conf. Properties Application of Dielectric Materials*, Seoul, Korea, 1997.
- [4] P. Holm, W. Rhyne, B. Gable, S. P. Rogers, K. Jachimowicz, F. Richard, and D. E. Ackley, "Two-dimensional LED arrays for virtual display image sources," *IEEE Trans. Electron Devices*, vol. 46, no. 5, pp. 897–904, May 1999.
- [5] R. M. A. Dawson, M. G. Kane, Z. Shen, D. A. Furst, S. Connor, J. Hsu, R. G. Stewart, and A. Ipri, "The impact of the transient of organic light emitting diodes on the design of active matrix OLED displays," in *IEDM Tech. Dig.*, 1998, pp. 875–878.
- [6] R. W. Chuang, A. Q. Zou, H. P. Lee, Z. J. Dong, F. F. Xiong, R. Shih, M. Bremser, and H. Juergensen, "Contact resistance of InGaN/GaN light emitting diodes grown on the production model multiwafer MOVPE reactor," *MRS Int. J. Nitride Semicond.*, 1999.
- [7] K. J. Tseng, S. Pan, and C. F. Foo, "Issues in power diode modeling for circuit simulation," in *Proc. Power Electronics Drive Systems*, vol. 1, May 1997, pp. 78–84.
- [8] T. Ytterdal, T. A. Fjeldly, M. S. Shur, S. M. Baier, and R. Lucero, "Enhanced Heterostructure field effect transistor CAD model suitable for simulation of mixed mode circuits," *IEEE Trans. Electron Devices*, vol. 46, no. 8, pp. 1577–1588, Aug. 1999.
- [9] J. Deng, B. Iñiguez, M. S. Shur, R. Gaska, M. A. Khan, and J. W. Yang, "Micro-wave simulations on the performance of GaN/AlGaIn HFETs," *Phys. Statist. Sol. (a)*, vol. 176, no. 1, pp. 205–208, 1999.
- [10] R. Gaska, Q. Chen, J. Yang, A. Osinsky, M. A. Khan, and M. S. Shur, "High-temperature performance of AlGaIn/GaN HFETs on SiC substrates," *IEEE Electron Devices Lett.*, vol. 18, no. 10, pp. 492–494, Oct. 1997.