The Third-Generation HP Thermal InkJet Printhead

The monolithic integration of driver transistors with the thermal inkjet heater resistors leads to vastly improved performance with reduced cost per page for the customer.

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For the third generation of HP thermal inkjet printers, three parameters were selected for significant improvement: print quality, print speed, and cost per printed page. Elsewhere in this issue, print quality and cost per page improvements are discussed. This article describes a printhead designed for the new HP DeskJet 1200C printer that permits a significant increase in the print swath with a corresponding increase in print speed.

Increasing print swath means more nozzles on the printhead from which to fire ink, hence a larger number of heater resistors. The printhead used in the current family of DeskJet printers (for example, the DeskJet 550C) has 50 nozzles and 50 corresponding heater resistors. The new printhead described here has 104 nozzles with 104 corresponding heater resistors. The direct drive technology used in the 50-nozzle printhead requires 54 interconnections between the printhead and the printer. A 104-nozzle printhead fabricated using the same direct drive technology would have some 112 interconnections between the printhead and the printer. By more than doubling the number of interconnections, the interconnect reliability would be compromised. Also, the size of the silicon chip would then be determined by the number of contact pads and would become uneconomically large.

Since a silicon chip is used to carry the passive thermal inkjet heater circuitry, simple MOS transistor drive circuitry was incorporated on the same substrate for the new 104-nozzle printhead. The name "integrated driver printhead" has been given to this combination. This integration reduces the number of interconnections required and thus the number of contact pads required on the integrated driver printhead.

Simplified direct drive and integrated drive circuits for a 20-nozzle printhead are compared in Fig. 1. These conceptual circuits can easily be extended to 104-nozzle printheads. Table I compares the various characteristics of the DeskJet 500C and DeskJet 1200C printheads. The 104-nozzle DeskJet 1200C printhead has only 36 interconnect pads whereas the direct drive 50-nozzle DeskJet 500C printhead has 54 interconnect pads. In spite of the larger print swath of the DeskJet 1200C printhead, its silicon chip size is comparable to that of the DeskJet 500C printhead and is significantly smaller than it would be if direct drive technology were used. Despite the increased complexity in using integrated drivers, the smaller silicon chip size leads to a lower cost per printhead than would be obtained with a direct drive printhead having the same print swath. This translates to a lower cost per page for the customer. In addition, the firing chamber geometry and the ink properties of the DeskJet 1200C printhead are optimized to increase the operating frequency (i.e., the number of ink drops fired per second). These improvements are discussed elsewhere in this issue.

Table I
Printhead Characteristics

	HP DeskJet 500C Printhead	HP DeskJet 1200C Printhead
Number of Nozzles	50	104
Number of Heater Resistors	50	104
Resolution (dpi)	300	300 by 600
Print Swath (in)	1/6	1/3
Number of Pads	54	36
Chip Size (mm × mm)	5.44 × 7.66	4.2 × 12.2

Demanding Environment

The integrated driver printhead is immersed in ink. The black ink is a pigmented ink with anionic dispersants. The color inks are based on anionic (sulfonated) dies. The inks also contain sodium, chlorine, and potassium. It is well-known that mobile sodium ions in the oxide layer of an MOS device can modify the threshold voltage and thereby destroy the device.[1] Because of the close proximity of the ink to the active devices and the elevated temperature during operation, ionic contamination was identified during the process selection stages of the integrated driver head development as a potential problem with an MOS integrated driver head. The inks also contain solvents that have been shown to cause failure in the mechanical components of thermal inkjet printheads. The new integrated driver head thin-film structure had to be proven insensitive to both of these potential problems. Life test and soak tests combined with device characterization were performed throughout the development whenever significant thin-film process or ink changes were made. Ionic contamination never surfaced as a problem—threshold voltages were always found to be stable with respect to ink exposure. However, tests proved to be valuable because they helped identify thin-film deposition process

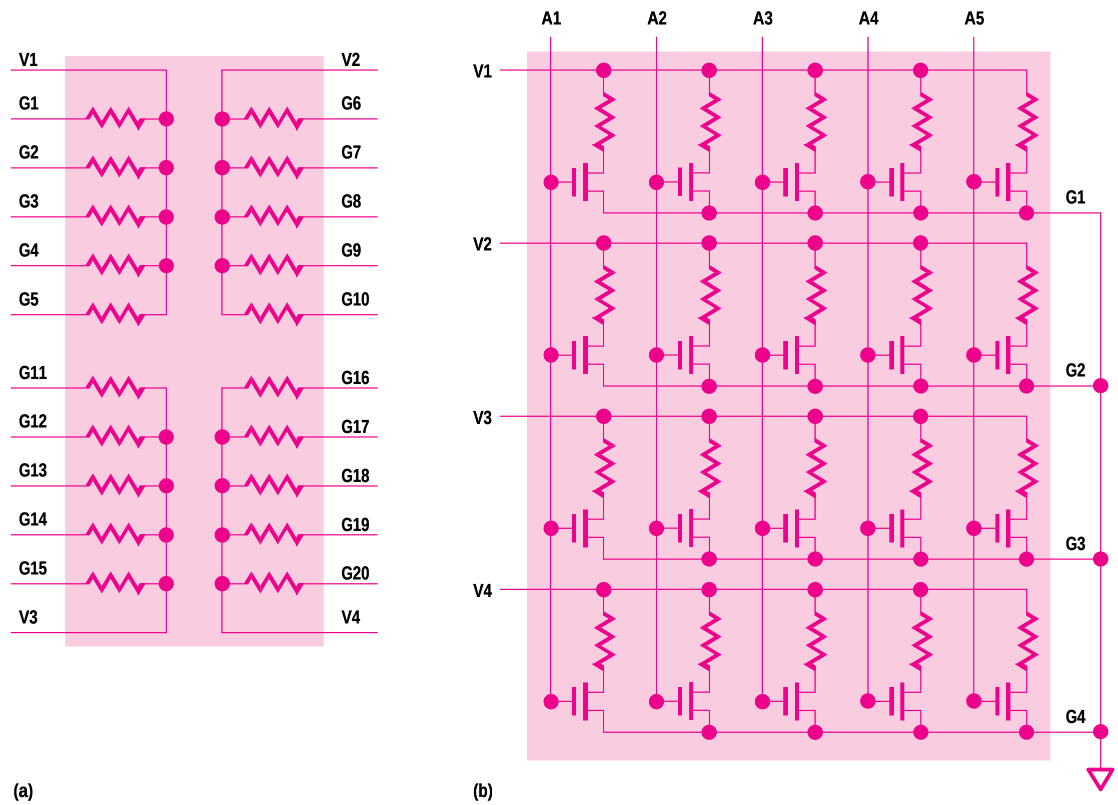

Fig. 1. Simplified drive circuits for a 20-nozzle printhead. (a) Direct drive, 24 lines. (b) Integrated driver printhead, 13 lines.

and materials combinations that produced the best film adhesion in the hot ink environment.

Thermal Cycling and Mechanical Cavitation

The thin-film heater resistors used in the integrated driver printhead are subjected to severe mechanical stresses during operation. These stresses arise from thermal cycling of the resistors and cavitation forces as the vapor bubbles collapse on various surfaces within the firing chambers. The thin-film resistor material is heated from near ambient temperature to well above the superheat temperature of water (the principal solvent in HP thermal inkjet inks) within several microseconds by each firing pulse. This results in large cyclic temperature gradients within the thin-film stack, in both the vertical and lateral directions. Thermal cycling to this extent creates extremely large mechanical stresses and therefore imposes a number of constraints on the thin-film materials used. In addition to chemical compatibility and thermal stability, the films above and below the resistor film must have stable, well-matched, film stresses to prevent cracking or delamination during operation.

During the cooling phase of each drop ejection cycle, the drive bubble collapses, allowing refill of the firing chamber with ink. While seemingly benign, the bubble collapse can create a microjet of fluid which causes large localized pressures on the surface it impacts. This process, known as cavitation, is difficult to observe directly, but it does produce pressures in excess of 130 atmospheres. If the firing chamber is incorrectly configured, these cavitation events can peen the protective films over the resistor and actually chip away portions of the film. Once damaged, the nucleation of subsequent bubbles is altered. If severe enough, this damage initiates a chain of events that can cause the resistor to break open and fail (see Fig. 2).

These mechanical stresses, which are unique to thermal inkjet technology, impose constraints on the integrated circuit chip in the integrated driver printhead, since the drive transistors share several films with the thermal inkjet portion of the device. The tantalum cavitation barrier is used as part of the metal interconnect. The dielectric passivation films that protect the firing resistors also protect the drive transistors and serve as the dielectric between the first-level and second-level metals. The resistor underlayer film, composed of SiO_2, also serves as the field isolation oxide in the NMOS drive transistors. Any film parameter adjusted to optimize the transistors is therefore likely to impact the thermal inkjet performance and vice versa. The resulting web of interactive variables complicates both the design and the process development.

High Current and Voltage

The pulses of electric energy delivered to the heater resistors to fire drops of ink are very small—they are measured in microjoules. However, the pulse of energy must be delivered in a very short amount of time for reasons of drop ejection performance and printer throughput. Because the ink-drop ejection rate is very high and because of the time it takes to demultiplex the firing pulses, only a small window of time is available for the firing of each drop. Since the pulse energy must be delivered in a period of several microseconds, the current flowing through the transistor when it is on is moderately high and the voltage across a transistor when it is off is also moderately high. The needs for high currents and voltages and small devices are in conflict. Thus, a significant

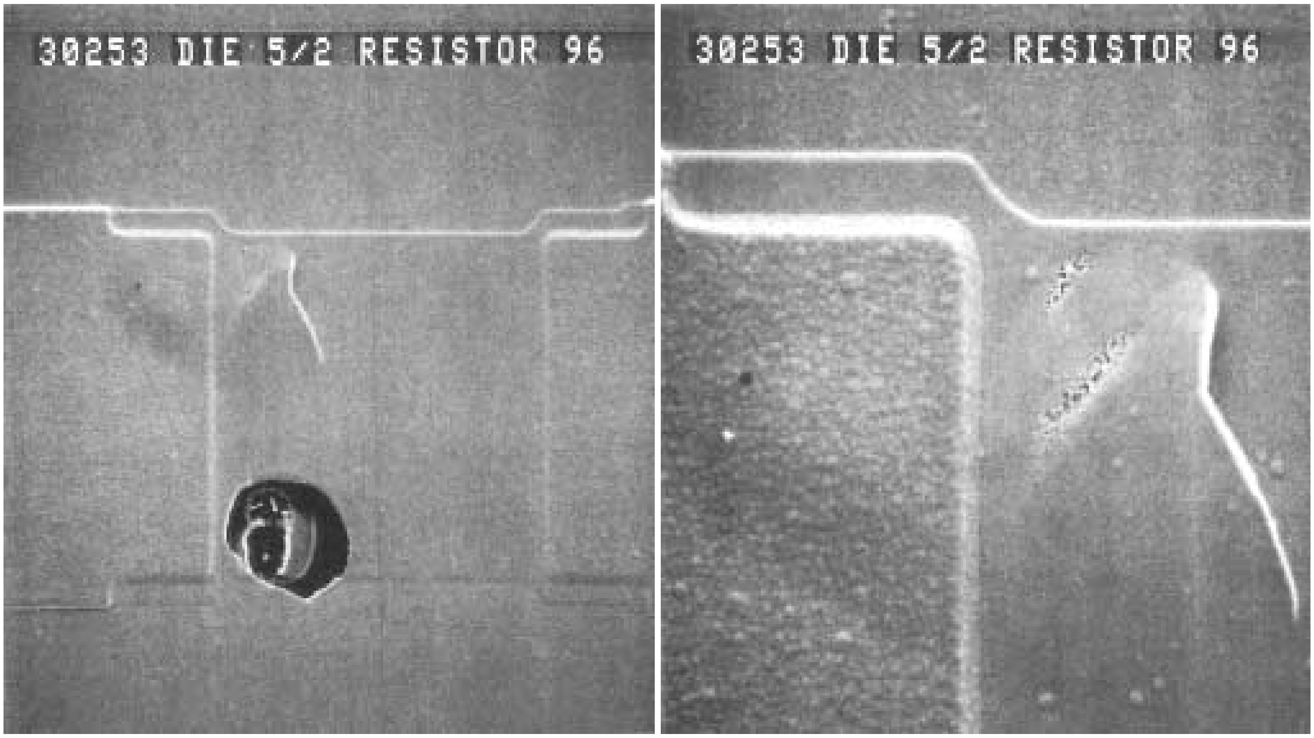

Fig. 2. Scanning electron micrographs of cavitation damaged resistors.

effort was required to select the process parameters and design rules for the new integrated driver printhead.

Electrostatic Discharge

The integrated driver printhead must be robust to electrostatic discharge (ESD) events. This requirement is a result of the unusual packaging of this type of device. The end user will need to replace the inkjet cartridge after the ink supply is exhausted. This type of handling, by printer users not necessarily familiar with ESD effects and precautions, potentially exposes the contacts on the print cartridge interconnect circuit to a variety of uncontrolled ESD events. This was addressed using a field plate diode ESD protection circuit to protect each ungrounded input pad.

Low-Cost, High-Yield, High-Volume Manufacturing

Perhaps the most fundamental constraints on the development of the integrated driver printhead are those imposed by commodity manufacturing. Since the print cartridges are user-replaceable, they must be manufactured in large volumes at low cost to support a continually growing installed base of printers, in addition to the units shipped with new printers. This approach requires very high-yielding, simple processing with a minimum number of process steps. Cost and simplicity assume relatively greater importance in tradeoffs with features and device performance than is typical for traditional IC processes.

Integrated Circuit Technology

The need for the driver circuitry and the thermal inkjet thin-film network to be electrically connected to each other on the same substrate presented a choice of switching transistor options (IC technologies such as bipolar, NMOS, etc.) as well as ways of combining or perhaps hybridizing the IC and thermal inkjet technologies. Since the second generation of thermal inkjet technology used an oxidized silicon substrate, it was decided that a monolithically integrated driver transistor and heater resistor circuit would be optimum. Because these printheads are replaced when the ink is depleted, it is important to use the lowest-cost process that will meet the printhead performance goals. Thus, a lower-cost three-mask NMOS process was selected over a five-mask bipolar process.

Several options were considered for the resistor addressing circuitry. The three most promising were row-column demultiplexing (demux), blocking diodes, and a proprietary passive enhanced multiplexing scheme. The row-column scheme was chosen and is shown in Figs. 1b and 3. This scheme reduces the number of pads from N to $2\sqrt{N}$ for a printhead with N resistors. Thus, the simplest 104-resistor printhead would require 21 pads. Additional ground and test pads raise the actual total on the DeskJet 1200C printhead to 36 pads.

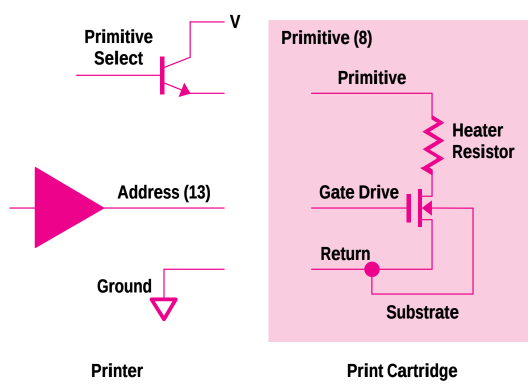

Fig. 3. Printer/printhead interface.

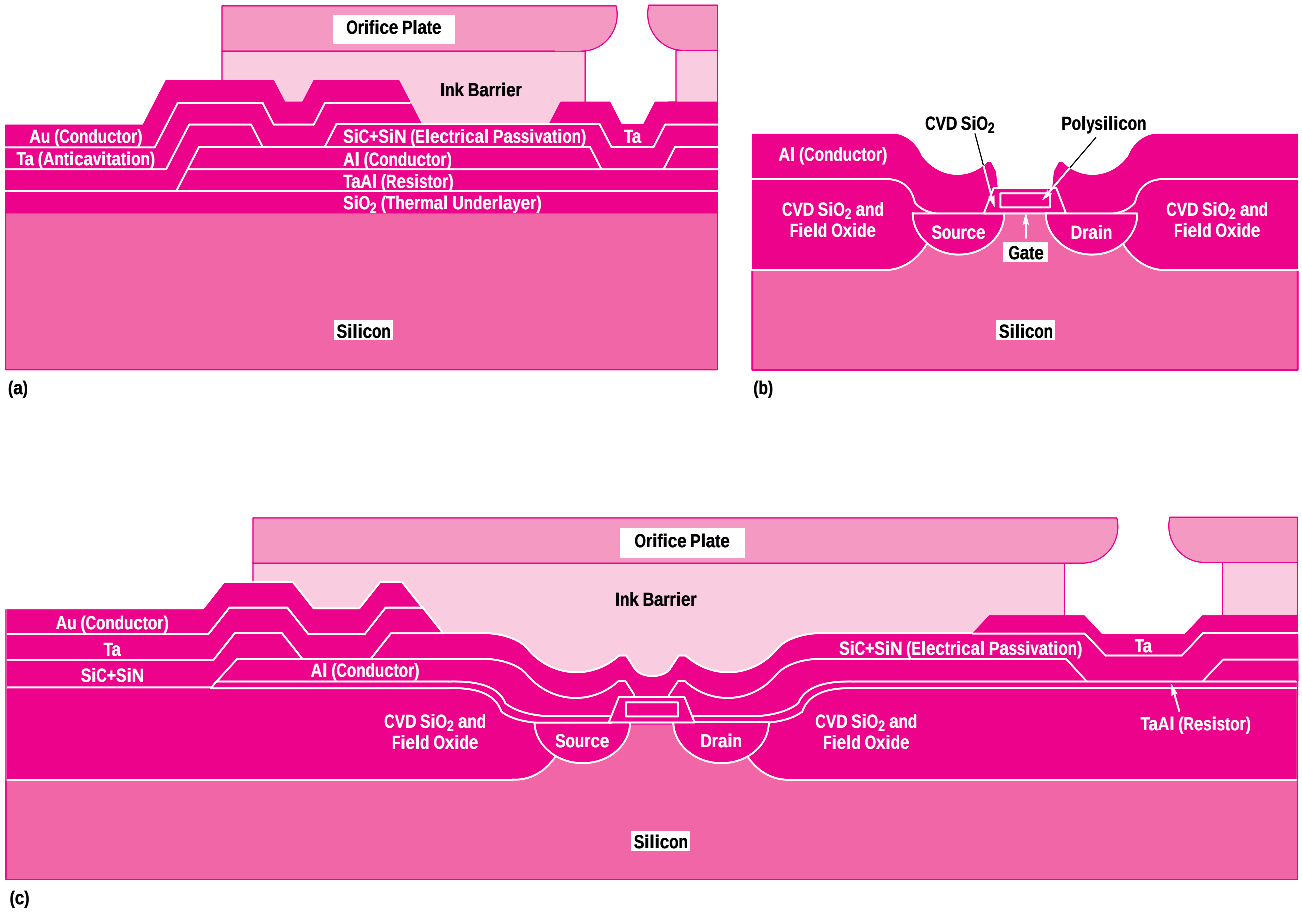

Fig. 4. (a) Thermal inkjet, (b) NMOS, and (c) merged technologies.

Process Implementation

From an IC process engineer's point of view, the existing thermal inkjet process (Fig. 4a) can be thought of as a special double-level metal interconnect process with an unusual interlevel dielectric, namely the SiN_x/SiC_y thermal inkjet passivation, and an upper interconnect level consisting of a thick refractory glue layer and a thinner noble bonding layer. If the first-level thermal inkjet conductor could also serve as the IC contacting metallization, and if the IC interlevel dielectric (see Fig. 4b) could be part of the thermal inkjet oxide underlayer, an elegantly simple process could be achieved. The resulting merged NMOS and thermal inkjet structure is shown in Fig. 4c.

To achieve this simplicity, it was necessary to draw on the strengths and flexibilities of both the IC and thermal inkjet technologies. Except that typical field oxides in NMOS technology are significantly thinner than the thermal isolation oxide required in thermal inkjet technology, these films are quite comparable. Thus, a thicker thermal oxide can serve both the thermal inkjet and NMOS requirements. However, NMOS requires an extra oxide layer for the interlayer dielectric between the polysilicon gate material and the first-level metal interconnect. To most beneficially incorporate this oxide into the merged NMOS and thermal inkjet technology, the total oxide underlayer in the merged technology is made up of the thermal field oxide and the chemical vapor deposited (CVD) SiO_2. This approach allows the use of a thinner thermal oxide layer with a correspondingly shorter growth time, and thus a lower cost.

NMOS technology with two levels of metal interconnect typically uses SiO_2 as the intermetal dielectric and Al as the second-level metal. This is not acceptable for the thermal inkjet structure. The dielectric and conductor layers directly above the thermal inkjet resistor must be thermally, chemically, and mechanically resistant to withstand the elevated temperatures required to boil the ink, the chemical reactivity of the hot ink, and the cavitation-induced mechanical stresses. The $SiN_x/SiC_y/Ta$ passivation layers used in Hewlett-Packard's passive thermal inkjet technology (introduced with the PaintJet and DeskJet printers in 1987 and 1988)[2,3] offer the required high performance and exceptional reliability. Thus, these films were selected to serve as the intermetal dielectric and the second-level metal in the integrated driver printhead structure.

The final process flow is shown in Fig. 5. Testing has demonstrated that when these materials and processes are used for the merged technologies, they maintain their robustness to the thermal inkjet environment while performing admirably in the role of a double-level metal NMOS IC process.

Manufacturability

Manufacturability is an important consideration in the design and development of a new product that is planned for high-volume production, but it is especially so when very low-cost fabrication is also a major goal. To address this issue, the integrated driver printhead process designers created a solution with the aim of addressing manufacturability at the outset. The circuit design rules were defined to

Start with p-type Silicon Substrate

Stress Relief Oxide Growth and Silicon Nitride Deposition

Pattern and Etch Islands

Field Oxide Growth

Remove Remaining Silicon Nitride and Thermal Oxide

Gate Oxide Growth

Polysilicon Deposition

Pattern and Etch Gate, Source, Drain

Gate, Source, Drain Doping

Phosphosilicate Glass Deposition and Densification

Pattern and Etch Contacts

TaAl/Al Deposition

Pattern and Etch Conductors and Resistors

Silicon Nitride and Silicon Carbide Passivation Deposition

Pattern and Etch Passivation Vias

Ta/Au Deposition

Pattern and Etch Ta/Au

Fig. 5. Integrated driver printhead process flow.

allow mixing lithographic equipment during the fabrication process. This also allowed the use of mature lithographic equipment. Yield management was also made significantly easier with these design rules.

Furthermore, where feasible, IC operations not required for this product were consolidated or dropped from the process. This created a very simple, low-cost NMOS IC process that could be integrated with the existing thermal inkjet process to meet all of the performance objectives of the product. However, many features of this merged process had not been attempted in a manufacturing environment. Significant efforts to address unexpected manufacturability issues were carried out during the prototyping phase of this project.

Summary

This article has described the successful merging of the well-established NMOS and thermal inkjet technologies in the new HP DeskJet 1200C printhead, resulting in low cost, excellent print quality, and high throughput. Many challenges were encountered in the integration of the two technologies, especially in the areas of multiple uses for the integrated circuit and thermal inkjet thin-film layers. These were successfully overcome through excellent teamwork among the IC process engineering, thermal inkjet process engineering, and printhead design teams from multiple HP divisions and sites. The keys to excellent teamwork and cooperation were communication, clear definition and understanding of goals, and ownership.

Acknowledgments

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References

1. A.S. Grove, *Physics and Technology of Semiconductor Devices,* John Wiley and Sons, Inc., 1967, p. 339.
2. *Hewlett-Packard Journal,* Vol. 39, no. 4, August 1988, pp. 6-56.
3. *Hewlett-Packard Journal,* Vol. 39, no. 5, October 1988, pp. 51-98.