Inkjet Technology: Principles, Materials, and Emerging Applications

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***Abstract*—Inkjet printing has evolved from a consumer technology to a versatile platform spanning industrial manufacturing, semiconductor processing, and biomedical applications. This tutorial reviews actuation principles, droplet formation physics, ink materials and system engineering, device structures, design and analysis methods, and representative applications. Emphasis is placed on practically useful ranges, co-design hints for MEMS/CMOS systems, and educational use. Future directions include Pb-free piezoelectrics, low-voltage actuation, digital-twin workflows, and bio-integration.**

***Index Terms*—Inkjet printing, piezoelectric actuation, thermal inkjet, EHD, Rayleigh–Plateau instability, MEMS nozzle, conductive ink, bio-printing, semiconductor processing, multi-physics modeling.**

I. Introduction

Since the 1970s, inkjet has progressed from home/office printers to an *industrial* method for maskless, material-efficient patterning. The shift was enabled by improved heads (MEMS nozzles, robust piezoelectric stacks), waveform design, and materials engineering. Today, inkjet bridges fluid mechanics, materials science, control engineering, and semiconductor device technology, making it both a practical manufacturing tool and an effective educational platform.

A. Historical Milestones

1950s: fundamentals of continuous inkjet; 1970s: thermal (bubble) inkjet; 1980s: commercial piezo inkjet; 2000s: industrial/functional printing; 2010s: bio-printing and 3D printing; 2020s: semiconductor assist, multi-material printing.

II. Actuation Principles

Three representative modes are used in practice.

A. Piezoelectric (Piezo)

A PZT transducer converts voltage into cavity deformation and pressure pulses. Typical drive is tens of volts to about 100 V with pulse widths of a few microseconds. Advantages: non-thermal, broad ink compatibility (including bio and nanoparticle inks), high reliability ($> 10^{10}$ shots).

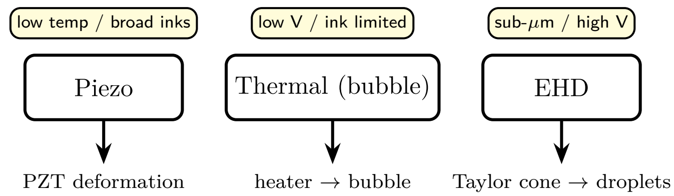

Fig. 1. Actuation principles: (left) piezoelectric deformation, (middle) thermal bubble expansion, (right) EHD Taylor cone.

TABLE I
Comparison of actuation modes

Mode	Voltage	Freq.	Reliability	Typical Use
Piezo	tens–100 V	up to ∼100 kHz	High	Industrial, bio
Thermal	10 V to 20 V	∼30 kHz	Medium	Home/office
EHD	>200 V	kHz	Early-stage	Nano-patterning

B. Thermal (Bubble Jet)

A micro-heater nucleates a vapor bubble whose expansion ejects a droplet. Drive voltage is low (10 V to 20 V) and the structure is simple and cost-effective, but ink choices are thermally constrained and lifetime is typically shorter than piezo heads.

C. Electrohydrodynamic (EHD)

A strong electric field forms a Taylor cone at the meniscus; sub-micron droplets can be produced at the expense of high voltage (hundreds of volts to kV) and lower throughput. Stability and safety remain challenges for wide industrial adoption.

III. Droplet Formation Physics

A short liquid column emitted from a nozzle breaks into droplets via the Rayleigh–Plateau instability. The fastest-growing disturbance wavelength is on the order of 4.5 times the jet diameter, guiding stable breakup and spacing.

A. Dimensionless Numbers

$$\mathrm{Re} = \frac{\rho U D}{\mu}, \qquad \mathrm{We} = \frac{\rho U^2 D}{\sigma}, \qquad \mathrm{Oh} = \frac{\mu}{\sqrt{\rho \sigma D}}. \qquad (1)$$

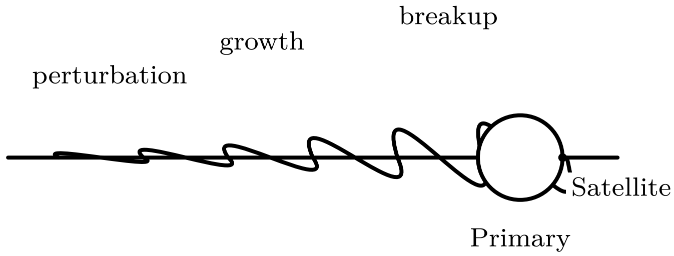

Fig. 2. Jet breakup: perturbation → growth → main drop and satellites.

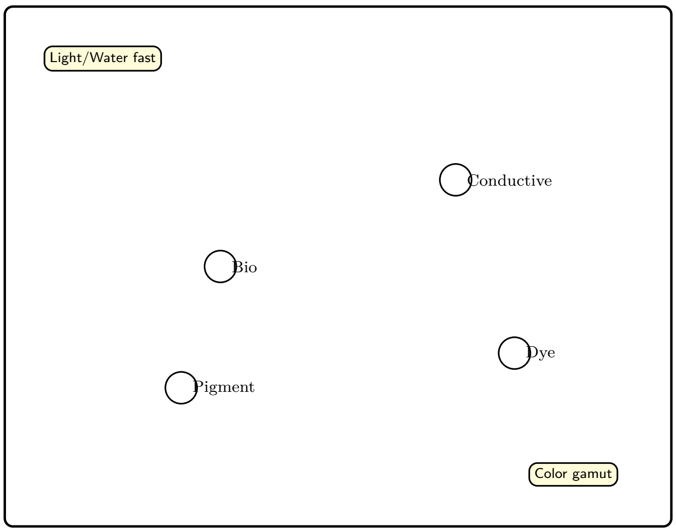

Fig. 3. Ink categories: dye, pigment, bio, and conductive.

Here ρ is density, U velocity, D nozzle diameter, μ viscosity, and σ surface tension. Stable printable regimes often satisfy $0.1 < \mathrm{Oh} < 1$ and $\mathrm{We} > 1$; too small Oh tends to generate satellites and too large Oh inhibits breakup.

B. Typical Operating Ranges

Nozzle diameter 10 ţm to 50 ţm, droplet velocity $1\,\mathrm{m\,s^{-1}}$ to $10\,\mathrm{m\,s^{-1}}$, droplet diameter 10 ţm to 80 ţm, Re $\sim$ 10–500, We $\sim$ 1–20, Oh $\sim$ 0.1–1.

C. Substrate Interaction

Post-impact spreading is governed by wettability; hydrophilic surfaces (contact angle $< 90°$) promote larger footprints, whereas hydrophobic surfaces confine spots. Surface treatments (plasma, SAMs, patterning) enable spatial control.

IV. Ink Materials

A. Classification

Dye-based: bright color, clog-resistant, lower durability. **Pigment-based**: high light/water fastness, needs dispersants and recirculation. **Bioinks**: cells/proteins/NA in aqueous media; viability and activity retention are critical. **Conductive inks**: Ag/Cu nanoparticles, CNT/graphene, or PEDOT:PSS; often require post-print sintering.

TABLE II
Typical ink property windows

Type	μ (mPa·s)	σ (mN/m)	Notes
Dye	2–5	30–40	vivid color
Pigment	5–15	25–35	durable, needs dispersants
Bio	2–20	30–50	viability/activity critical
Conductive	10–20	25–40	sintering needed

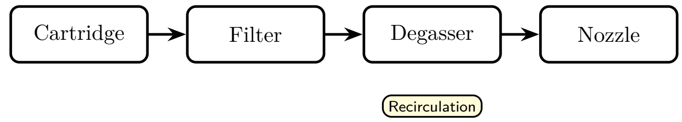

Fig. 4. System flow: cartridge → filter → degassing → recirculation → nozzles.

TABLE III
System trade-offs

Element	Desirable	Challenge
Filter	Remove particles	Clogging risk
Degassing	Stable ejection	Cost/complexity
Recirculation	Anti-sedimentation	Pressure loss
Neg. pressure	No drip	Misfire risk if excessive

B. Key Properties

Viscosity typically $2\,\mathrm{mPa\,s}$ to $20\,\mathrm{mPa\,s}$; surface tension $25\,\mathrm{mN\,m^{-1}}$ to $50\,\mathrm{mN\,m^{-1}}$; density around $1000\,\mathrm{kg\,m^{-3}}$ (aqueous). Volatility affects nozzle dry-out and on-substrate leveling.

C. Bio Considerations

For piezo printing, cell viability of 80–95% is achievable with careful shear/pressure management. Proteins benefit from non-thermal actuation and stabilizers (e.g., glycerol, trehalose).

V. Ink System Engineering

A. Components

Cartridge (level sensing, anti-bubble design), filter (0.2–1 ţm), degassing (vacuum or membrane), and recirculation (preventing sedimentation/aging).

B. Controls

Reservoir pressure regulation (precision within hundreds of Pa), slight negative pressure at the nozzle to avoid self-dripping, nozzle dry-out prevention (capping, purge, humidity), and ejection stabilization (temperature control, synchronized pressure-waveform).

VI. Device Structures and Materials

A. Nozzles and Cavities

Silicon (DRIE, thin-film stacks): high precision and MEMS maturity. **Glass** (laser drilling, anodic bonding): chemical stability, low moisture uptake. **Polymer** (SU-8/PI/parylene): low-cost prototyping, bio-friendly processing.

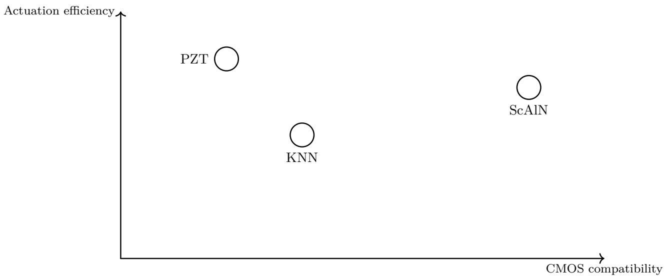

Fig. 5. Piezoelectric materials for actuation (PZT, KNN, ScAlN).

TABLE IV
PIEZOELECTRIC MATERIAL SNAPSHOT

Material	Displacement	CMOS	Environment	Note
PZT	**High**	△	△	Industry standard
KNN	Medium	△	**Good**	Pb-free candidate
ScAlN	Med–High	**Good**	**Good**	Thin-film, RF

B. Piezoelectric Materials

PZT: high d_{31}/d_{33}, proven reliability; RoHS exemptions typically apply for piezo use. **KNN** (Pb-free): promising d_{33}, sintering/process window challenging. **ScAlN** (thin film): CMOS-compatible sputtering, enhanced $e_{31,f}$, good for high-frequency thin actuators.

C. Integration with CMOS

Thousands of channels require HV level shifters, charge-recycling, tight skew control (sub-ţs), and careful EMC/ESD design. 2.5D/3D integration reduces parasitics and preserves waveform fidelity; thermal management becomes critical.

D. Protection, Sealing, Reliability

Hydrophobic anti-wetting (e.g., fluorinated coatings) stabilizes the meniscus; barrier layers ($SiN/SiC/DLC/Al_2O_3$) protect against corrosion/erosion. Reliability concerns include mechanical fatigue (10^9–10^{11} cycles), cavitation/erosion under steep waveforms, thin-film delamination, and bubble/particle tolerance.

VII. DESIGN AND ANALYSIS APPROACHES

A. Modeling Stack

0D/1D: Equivalent RLC acoustic models with an electro-mechanical transformer representing the piezo; fluid impedance

$$Z_f(\omega) \approx R + j\omega L + \frac{1}{j\omega C}. \tag{2}$$

2D/3D FEM: modal analysis (resonance/anti-resonance), displacement fields, cavity pressure response. **CFD/FSI**: level-set/VOF for meniscus motion, jetting, breakup, and impact.

TABLE V
APPLICATION SUMMARY

Domain	Use	Advantage	Challenge
Printing	Commercial photo	High dpi	Throughput, durability
Electronics	Circuits/electrodes	Maskless, flexible	Sintering, uniformity
Semiconductor	Films, RDL, patterning assist	Material savings	Alignment, CD control
Bio	Cells/proteins	Precise placement	Viability, activity

B. Meshing and Numerics

Spatial resolution near the free surface $\leq D/50$; time step $\Delta t \lesssim 0.1D/\sqrt{\sigma/(\rho D)}$. Distinguish advancing/receding contact angles (e.g., 80°/110°). Include finite compressibility of the cavity liquid for accurate acoustic coupling.

C. Waveform Design

Bipolar/multi-pulse patterns: *push* (jet formation), *dwell* (pressure settle), *pull* (meniscus recovery, satellite suppression), and *damp* (ringing control). Charge recycling reduces power; per-nozzle calibration corrects variation.

VIII. APPLICATIONS

A. Printing

High-resolution digital printing (>1200 dpi), on-demand variable data printing, packaging.

B. Printed Electronics

Ag/Cu nanoparticle interconnects, RFID antennas, transparent electrodes, and energy devices. Post-print sintering and sheet resistance uniformity are key.

C. Semiconductor Manufacturing

Localized deposition of insulating films, RDL metallization, and patterning assist (defect repair, resist trimming). Alignment and feature-size control are the main challenges.

D. Biotechnology

Cell printing for tissue models and drug screening; protein microarrays with nL–pL consumption. Maintain viability and activity via non-thermal actuation and gentle waveforms.

Domain	Throughput	Uniformity	Alignment	Viability
Bio				•
Printing	•	•		
Electronics			•	
Semiconductor		•	•	

Fig. 6. Application landscape across domains.

IX. Educational Insights

Inkjet provides rare, direct links between theory and practice across fluid mechanics (instability, scaling), materials (ink formulation, piezoelectrics), control (waveforms, pressure/temperature), and semiconductor engineering (MEMS/CMOS integration). Example exercises include (i) computing Re, We, Oh and assessing printability; (ii) RLC-based system analysis; (iii) droplet simulation vs. measured dropwatch data.

Suggested Exercises

1) **Dimensionless Analysis:** Given nozzle diameter $D = 30$ ţm, droplet velocity $U = 5\,\mathrm{m/s}$, viscosity $\mu = 3\,\mathrm{mPa \cdot s}$, density $\rho = 1000\,\mathrm{kg/m^3}$, and surface tension $\sigma = 35\,\mathrm{mN/m}$, calculate Re, We, and Oh. Discuss whether this condition falls in the printable regime.
2) **Waveform Optimization:** Design a bipolar voltage waveform sequence (*push–dwell–pull–damp*) for a piezo actuator, targeting droplet volume $20\,\mathrm{pL}$ with minimal satellites. Justify the expected effect of each phase.

X. Conclusion

Inkjet matured into a platform technology for printing, electronics, semiconductors, and biotechnology. Progress will hinge on eco-friendly materials (Pb-free piezoelectrics), low-power actuation and charge recycling, reliability engineering, and data-driven design (digital twins, AI-based waveform optimization).

Research Outlook (Next 5–10 Years)

- **Pb-free piezoelectrics:** Scalable KNN, ScAlN thin films, and composite stacks for sustainable actuators.
- **Low-voltage operation:** Integration of high-efficiency MEMS transducers enabling $< 10\,\mathrm{V}$ drive.
- **Multi-material integration:** Hybrid printing of functional inks (semiconductor, bio, conductive).
- **Digital-twin workflows:** Coupling CFD/FEM with machine learning for predictive jetting models.
- **Bio-integration:** Tissue printing, organ-on-chip, and personalized medicine applications.

Acknowledgment

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Appendix: Repository Context (Illustrative Figures)

This appendix illustrates the repository organization and workflow supporting this tutorial. The project relies on open and reproducible infrastructure so that manuscripts, figures, and automated builds can be consistently maintained and extended. This structure enhances both transparency and reusability, allowing the same materials to be used for research dissemination as well as for educational purposes.

In particular:

- The `papers/` directory organizes multiple manuscripts and their associated figures.
- The `.github/workflows/` directory contains automated PDF build pipelines using GitHub Actions.
- The `figs/` directory centralizes TikZ sources, raster images, and supporting artwork.

Such repository design improves reproducibility of the tutorial figures and tables, and facilitates efficient collaboration and continuous revision.

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