Op Amp Technology Overview

Developed by Art Kay, Thomas Kuehl, and Tim Green
Presented by Ian Williams
Precision Analog – Op Amps
Bipolar vs. CMOS / JFET

• Transistor technologies
  – Bipolar, CMOS and JFET

• Vos and Ib and Drift
  – Laser Trim, Package Trim, and Zero Drift

• Noise
  – JFET, MOSFET, and Bipolar (1/f noise)

• Input Structures
  – Rail-to-Rail, Charge Pump
  – Chopper (Zero-Drift)
    • Chopper Noise Sources
  – Input crossover distortion
  – Input back-to-back diodes

• Output Structures – The “Claw Curve”
  – Rail-to-Rail vs. Non Rail-to-Rail
  – Open Loop Output Impedance, Zo

• Bandwidth

• Summary
Bipolar, CMOS, JFET (Op Amp input device structures)

1) **Current Controlled Device**
2) “Current Controlled Current Source”
3) \( I_c = I_b \times hfe \)
4) \( I_b = 0A \) turns bipolar off
5) Base is op amp +/- input
6) Highest Op Amp input current

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1) **Voltage Controlled Device**
2) “Voltage Controlled Resistor”
3) \( V_{gs} > 2V \) controls \( R_{ds\_on} \)
4) \( V_{gs} = 0V \) turns MOSFET off
5) Gate is op amp +/- input
6) Very Low Op Amp input current

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1) **Voltage Controlled Device**
2) “Voltage Controlled Resistor”
3) \( 0V < V_{gs} < -2V \) controls \( R_{ds\_on} \)
4) \( V_{gs} < -2V \) turns JFET off
5) Gate is op amp +/- input
6) Very Low Op Amp input current
Vos & Ib: Model and Hand Calculations

- Voltage offset adds a dc error to Vout
- The offset contributed is unique to each device

\[ R_{eq} = \frac{R_f \cdot R_1}{R_f + R_1} \]

\[ G_n = \frac{R_f}{R_1} + 1 \]

\[ V_{o\_vos} = V_{os} \cdot G_n \]

\[ V_{o\_ib+} = I_b \cdot R_s \cdot G_n \]

\[ V_{o\_ib-} = I_b \cdot R_{eq} \cdot G_n \]

\[ V_{o\_os\_ib} = V_{o\_vos} + V_{o\_ib+} + V_{o\_ib-} \]
What’s inside the Amplifier – Bipolar vs. CMOS

Bipolar input op amp

CMOS input op amp

Trim these resistors for Vos & Vos drift for CMOS

Trim these resistors for Vos & Vos drift for Bipolar

Vin1

R1

R2

Cc

Unity Gain

Vcc

Q1

Q2

R_{os1}

R_{os2}

Vin2

IS1

Vout

Vcc

R1

R2

Q1

Q2

R_{os1}

R_{os2}

Vin1

IS1

Vin2

I_{b2}
# Bipolar and CMOS

<table>
<thead>
<tr>
<th>Model</th>
<th>Technology</th>
<th>Rail-to-rail</th>
<th>Supply V+ to V-</th>
<th>Op Current typ</th>
<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA211</td>
<td>Bipolar</td>
<td>RRO</td>
<td>4.5 - 36 V</td>
<td>3.6 mA</td>
<td>60 uV</td>
<td>0.35 uV/°C</td>
<td>60 nA</td>
<td>1.1 nV/√Hz</td>
<td>45 MHz</td>
<td>27 V/us</td>
</tr>
<tr>
<td>OPA350</td>
<td>CMOS</td>
<td>RRIO</td>
<td>2.7 - 5.5 V</td>
<td>5.2 mA</td>
<td>150 uV</td>
<td>4 uV/°C</td>
<td>0.5 pA</td>
<td>16 nV/√Hz</td>
<td>38 MHz</td>
<td>22 V/us</td>
</tr>
</tbody>
</table>

- OPA2x11 - Ultra low Noise, low power, precision op amp
  - Ideal for driving high-precision 16-bit ADCs or buffering the output of high-resolution digital-to-analog converters DACs
- OPAx350 High-Speed, Single-Supply, Rail-to-Rail I/O
  - High-performance ADC driver, very high $C_{\text{Load}}$ drive capability
Inherent Drift of Bipolar vs. CMOS

- Drift is proportional to offset
- When $V_{os}$ trimmed to zero, drift is near zero.
- Simple one step trim: just trim offset
- Frequently more curvature than bipolar
- When $V_{os}$ trimmed to zero, drift remains.
- More complex two part trim: drift first, then offset
- Offset and drift trims interact, difficult to optimize both
Laser Trim – What does it look like?

- Bipolar, CMOS, JFET can be used
  - Only way to trim bipolar
- Trimmed in wafer form before package
- Laser makes narrow cuts in resistor
- Increases resistance continuously
- Circuit can be active, but laser may disturb circuit function—requires cutting in bursts (long test time)
- Generally each trim has a pair of resistors for bidirectional trim
Bipolar vs. CMOS
Op amps that utilize thin-film resistor laser trimming for improved offset and drift

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<tr>
<th>Model</th>
<th>Technology</th>
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<th>Supply V+ to V-</th>
<th>Op Current typ</th>
<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA1612</td>
<td>Bipolar</td>
<td>Out</td>
<td>4.5 – 36 V</td>
<td>3.6 mA</td>
<td>100 uV</td>
<td>1 uV/°C</td>
<td>60 nA</td>
<td>1.1 nV/√Hz</td>
<td>40 MHz</td>
<td>27 V/us</td>
</tr>
<tr>
<td>OPA320S</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>1.8 – 5.5 V</td>
<td>1.5 mA</td>
<td>40 uV</td>
<td>1.5 uV/°C</td>
<td>0.2 pA</td>
<td>8.5 nV/√Hz</td>
<td>20 MHz</td>
<td>10 V/us</td>
</tr>
</tbody>
</table>

• **OPA1612 - SoundPlus™ High-Performance, Bipolar-Input Audio Op Amp**
  - Achieves very low noise density with an ultralow distortion of 0.000015% at 1 kHz.
  - Rail-to-rail output swing to within 600 mV with a 2-kΩ load

• **OPA320S - 20-MHz, Low-Noise, RRl/O, Low operating current, with shutdown**
  - A combination of very low noise, high gain-bandwidth, and fast slew make it ideal for signal conditioning and sensor amplification requiring high gain
Package level electronic trim, e-trim™

- CMOS op amps only due to digital circuitry requirements
- Standard pinout
  - Trim data is entered through output current load
- Blow and set internal fuses
- Disable trim mechanism after the trim is completed
  - No customer access to trim function
- Programmed fuses are read at each power-on
### Model Specifications

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</thead>
<tbody>
<tr>
<td>OPA376</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>2.2 – 5.5 V</td>
<td>760 uA</td>
<td>5 uV</td>
<td>0.26 uV/°C</td>
<td>0.2 pA</td>
<td>7.5 nV/√Hz</td>
<td>5.5 MHz</td>
<td>2 V/us</td>
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<tr>
<td>OPA192</td>
<td>HV CMOS</td>
<td>RRIO</td>
<td>8 – 36 V</td>
<td>1 mA</td>
<td>5 uV</td>
<td>0.1 uV/°C</td>
<td>5 pA</td>
<td>5.5 nV/√Hz</td>
<td>10 MHz</td>
<td>20 V/us</td>
</tr>
</tbody>
</table>

- **OPA376** – Precision, Low-noise, Low offset, Low quiescent current
  - Well-suited for driving SAR ADCs as well as 24-bit and higher resolution converters
- **OPA192** - Precision, 36 V, Low offset, Fast slewing
  - differential input-voltage range to the supply rail
  - high output current (±65 mA)
What’s inside the Amplifier – Bipolar vs. CMOS

Bipolar input op amp

CMOS input op amp

Ib from diode leakage Ib ≈ ±1pA

Ib from base current ≈ 100nA

Bipolar input does have ESD cells, but Ib >> I_{leak}
Bipolar - Bias Current Cancellation

Bipolar IB

<table>
<thead>
<tr>
<th>Uncancelled</th>
<th>100nA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancelled</td>
<td>1nA</td>
</tr>
</tbody>
</table>
Bipolar - Bias Current Cancellation

Cancellation vs non-cancellation

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<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA209</td>
<td>Bipolar with Ib cancel</td>
<td>RRO</td>
<td>4.5 - 36 V</td>
<td>2.2 mA</td>
<td>35 uV</td>
<td>0.05 uV/°C</td>
<td>1 nA typ 4.5 nA max</td>
<td>2.2 nV/√Hz</td>
<td>18 MHz</td>
<td>6.4 V/us</td>
</tr>
<tr>
<td>OPA211</td>
<td>Bipolar w/o Ib cancel</td>
<td>RRO</td>
<td>4.5 - 36 V</td>
<td>3.6 mA</td>
<td>60 uV</td>
<td>0.35 uV/°C</td>
<td>60 nA typ 175 nA max</td>
<td>1.1 nV/√Hz</td>
<td>45 MHz</td>
<td>27 V/us</td>
</tr>
</tbody>
</table>

- OPA209 – 36 V, low power, noise, offset, drift and input bias current
  - Suitable for fast, high-precision applications. Has fast settling time to 16-bit accuracy
- OPA2x11 - Ultra low Noise, low power, precision op amp
  - Ideal for driving high-precision 16-bit ADCs, or buffering the output of high-resolution DACs
Bipolar vs. CMOS bias current drift (Ib vs Temp)

Bipolar amplifier:
In this case you see a dramatic increase in bias current at 75 °C.

CMOS amplifier:
In this case you see a dramatic increase in bias current at 25 °C. Note the logarithmic graph, which doubles every 10 °C.
CMOS: $I_{n_{350}} = 4fA/\sqrt{\text{Hz}}$

JFET: $I_{n_{827}} = 2.2fA/\sqrt{\text{Hz}}$

Bipolar: $I_{n_{277}} = 200fA/\sqrt{\text{Hz}}$

Note: CMOS current noise has minimal $1/f$, but it may be significant in bipolar
## JFET, Bipolar, and CMOS Noise

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<tr>
<th>Model</th>
<th>Technology</th>
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<th>Supply V+ to V-</th>
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<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA827</td>
<td>JFET + Bipolar</td>
<td>No</td>
<td>8 – 36 V</td>
<td>4.8 mA</td>
<td>75 uV</td>
<td>0.1 uV/°C</td>
<td>3 pA</td>
<td>4 nV/√Hz</td>
<td>22 MHz</td>
<td>28 V/us</td>
</tr>
<tr>
<td>OPA227</td>
<td>Bipolar</td>
<td>No</td>
<td>10 – 36 V</td>
<td>3.7 mA</td>
<td>10 uV</td>
<td>0.3 uV/°C</td>
<td>2.5 nA</td>
<td>3 nV/√Hz</td>
<td>8 MHz</td>
<td>2.3 V/us</td>
</tr>
<tr>
<td>OPA350</td>
<td>CMOS</td>
<td>RRIO</td>
<td>2.7 – 5.5 V</td>
<td>5.2 mA</td>
<td>150 uV</td>
<td>4 uV/°C</td>
<td>0.5 pA</td>
<td>16 nV/√Hz</td>
<td>38 MHz</td>
<td>22 V/us</td>
</tr>
</tbody>
</table>

- **OPA827 - Low-Noise, High-Precision, JFET-Input**
  - Precision 16-bit to 18-bit mixed signal systems, transimpedance amplifiers

- **OPA227 - High Precision, Low Noise**
  - Ideal for applications requiring both AC and precision DC performance

- **OPAx350 High-Speed, Single-Supply, Rail-to-Rail I/O**
  - High-performance ADC driver, very high $C_{\text{Load}}$ drive capability
### OPA703 Complementary CMOS – Rail-to-Rail

#### PARAMETER

<table>
<thead>
<tr>
<th>INPUT VOLTAGE RANGE</th>
<th>CONDITION</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common-Mode Voltage Range</td>
<td>$V_{CM}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common-Mode Rejection Ratio</td>
<td>$V_{CM}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>over Temperature</td>
<td>$V_S = \pm 5V$, $(V^-) - 0.3V &lt; V_{CM} &lt; (V^+) + 0.3V$</td>
<td>70</td>
<td>90</td>
<td>$(V^+)$ + 0.3</td>
<td>V</td>
</tr>
<tr>
<td>over Temperature</td>
<td>$V_S = \pm 5V$, $(V^-) &lt; V_{CM} &lt; (V^+)$</td>
<td>68</td>
<td>96</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>over Temperature</td>
<td>$V_S = \pm 5V$, $(V^-) - 0.3V &lt; V_{CM} &lt; (V^+) - 2V$</td>
<td>80</td>
<td>96</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>over Temperature</td>
<td>$V_S = \pm 5V$, $(V^-) &lt; V_{CM} &lt; (V^+) - 2V$</td>
<td>74</td>
<td>96</td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

#### Diagram

**Common Mode Voltage** ($V$)
- $200$ V
- $100$ V
- $0$ V
- $-100$ V
- $-200$ V
- $-300$ V

**Input Offset Voltage** ($\mu V$)
- $200$ µV
- $100$ µV
- $0$ µV
- $-100$ µV
- $-200$ µV
- $-300$ µV

**Graph**
- Input Offset Voltage (µV) vs. Common Mode Voltage (V)
## Complementary CMOS – Rail-to-Rail

### Abrupt offset change at input P-ch/ N-ch switchover point

<table>
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<tr>
<th>Model</th>
<th>Technology</th>
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<th>Supply V+ to V-</th>
<th>Op Current typ</th>
<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA703</td>
<td>12 V CMOS</td>
<td>RRIO</td>
<td>4 - 12 V</td>
<td>160 uA</td>
<td>35 uV</td>
<td>4 uV/°C</td>
<td>1 pA</td>
<td>45 nV/√Hz</td>
<td>1 MHz</td>
<td>0.6 V/us</td>
</tr>
<tr>
<td>OPA314</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>1.8 – 5.5 V</td>
<td>150 uA</td>
<td>60 uV</td>
<td>1 uV/°C</td>
<td>0.4 pA</td>
<td>14 nV/√Hz</td>
<td>2.7 MHz</td>
<td>1.5 V/us</td>
</tr>
</tbody>
</table>

**Graphs:**

- **OPA703** 0 to +5 V input, $V_s \pm 5$ V
- **OPA314** ±2.75 V input, $V_s \pm 2.75$ V
Input Crossover Distortion

**Vout vs. Time**

- **Vout** (Volts) vs. **time** (ms)

**Vout vs. Time (Zoomed In)**

- **Vout** (Volts) vs. **time** (ms)
- Green line: Vout Ideal
- Red line: Vout Crossover

**Input Offset Voltage**

- **Input Offset Voltage (mV)** vs. **time** (ms)

**Common Mode Voltage**

- **Common Mode Voltage (V)** vs. **time** (ms)

![Circuit Diagram](image-url)
OPA365 MOSFET Charge Pump – Rail-to-Rail

\[ V_{\text{OUT}} = +V_S + 1.8V \]

- Uses charge pump to raise \( V^+ \) rail and overcome \( V_{\text{sat}} \) + \( V_{\text{gs}} \) of input PMOS FETs
- Charge pump switches at 10 MHz which is within op amp 50 MHz GBW
- Pump design is patented and has very low ripple
- Charge pump noise is small relative to broadband noise
### MOSFET Charge Pump – Rail-to-Rail
Eliminates input stage crossover distortion

<table>
<thead>
<tr>
<th>Model</th>
<th>Technology</th>
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<th>Supply V+ to V-</th>
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<th>Offset typ</th>
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<th>Voltage noise 1 kHz</th>
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<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA365</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>2.2 – 5.5 V</td>
<td>4.6 mA</td>
<td>100 uV</td>
<td>1 uV/°C</td>
<td>0.2 pA</td>
<td>12 nV/√Hz</td>
<td>50 MHz</td>
<td>25 V/us</td>
</tr>
<tr>
<td>OPA322</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>1.8 – 5.5 V</td>
<td>1.5 mA</td>
<td>500 uV</td>
<td>1.5 uV/°C</td>
<td>0.2 pA</td>
<td>8.5 nV/√Hz</td>
<td>20 MHz</td>
<td>10 V/us</td>
</tr>
</tbody>
</table>

- **OPA365 – Wide bandwidth, Low-Distortion, High CMRR**
  - High performance optimized for low voltage, single-supply applications
- **OPA322 – Wide bandwidth, Low-Noise, Low current**
  - Optimized for low noise and wide bandwidth while requiring low quiescent current
“Chopper” and “Zero-Drift” CMOS Op Amps use complementary input P-ch/ N-ch concept with Digital Calibration for Offset Correction
Comparing Common Architectures vs. Chopper

<table>
<thead>
<tr>
<th>CMOS Vos/drift</th>
<th>Typ Vos (uV)</th>
<th>Typ Drift (uV/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>Zero Drift</td>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>(chopper)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Trim</td>
<td>10</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Chopper Amplifying Vin

- Vin inverted at the input and output every other calibration cycle
- Overall signal path doesn’t see an inversion
Chopper Amplifying Vos

- Vos only inverted at output every other calibration cycle
- Offset translates to triangle wave
- Offset average is zero
- Sync Filter eliminates triangle wave

\[ f = 125\text{kHz on OPA333} \]
Average = 0
Slope = \( \frac{V_{os} \cdot g_m}{C_c} \)
Chopper: A more complete diagram
Chopper Noise Sources and Ib

OPA188 IB – Chopper Calibration Feedthrough

![Graph showing chopper noise sources and Ib](image)

- **Ib(Average) = 160pA**
- **611ns**

OPA188 Noise Density vs. Frequency

- **No 1/f Noise**
- **Chopper Noise Feedthrough**
Chopper Op Amps

Chopper techniques provide low offset voltage and near zero-drift over time and temperature

<table>
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<tr>
<th>Model</th>
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<th>Rail-to-rail</th>
<th>Supply V+ to V-</th>
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<th>Offset typ</th>
<th>Offset drift typ</th>
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<th>Voltage noise 1 kHz</th>
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<th>Slew rate</th>
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</thead>
<tbody>
<tr>
<td>OPA333</td>
<td>LV CMOS</td>
<td>RRIO</td>
<td>1.8 – 5.5 V</td>
<td>17 uA</td>
<td>2 uV</td>
<td>0.02 uV/°C</td>
<td>70 pA</td>
<td>55 nV/√Hz</td>
<td>350 kHz</td>
<td>0.16 V/us</td>
</tr>
<tr>
<td>OPA188</td>
<td>HV CMOS</td>
<td>RRO</td>
<td>4- 36 V</td>
<td>425 uA</td>
<td>6 uV</td>
<td>0.03 uV/°C</td>
<td>160 pA</td>
<td>8.8 nV/√Hz</td>
<td>2 MHz</td>
<td>0.8 V/us</td>
</tr>
</tbody>
</table>

• OPA333 - 1.8 V, Precision, microPower
  – Provides excellent CMRR without the crossover associated with traditional complementary input stages

• OPA2188 – 36 V, Precision, Low-Noise, Rail-to-Rail Output
  – Offers very low offset and drift with high CMRR, PSRR, and AOL performance
Input Stage Back-to-Back Diodes

**CMOS**: May not be needed, Check Data Sheet.
**JFET**: May not be needed, Check Data Sheet.
**Bipolar**: Generally Required.

These diodes prevent overstress damage on input base to emitter junctions.

- Diodes can cause problems in multiplexed applications
- See TIPD151 for details
The diodes can turn on during slewing and cause very large $I_b$. Can be a significant problem in Mux applications (TIPD151).
Input Stage Back-to-Back Diodes
Op amps with differential input over-voltage protection

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<tr>
<td>OPA171</td>
<td>HV CMOS</td>
<td>RRO</td>
<td>2.7 - 36 V</td>
<td>475 uA</td>
<td>250 uV</td>
<td>0.3 uV/°C</td>
<td>8 pA</td>
<td>14 nV/√Hz</td>
<td>3 MHz</td>
<td>1.5 V/us</td>
</tr>
<tr>
<td>OPA1622</td>
<td>Bipolar</td>
<td>No</td>
<td>4 – 36 V</td>
<td>2.6 mA</td>
<td>100 uV</td>
<td>0.5 uV/°C</td>
<td>1.2 uA</td>
<td>2.8 nV/√Hz</td>
<td>8 MHz</td>
<td>10 V/us</td>
</tr>
</tbody>
</table>

- **OPAx171** - 36-V, Single-Supply, SOT553, General-Purpose Op Amps
  - single-supply, low-noise, low offset and drift, and low quiescent current
- **OPA1622** - SoundPlus™ High-Fidelity, Bipolar-Input, Audio Op Amp
  - very low noise density, with an ultralow THD+N of -119.2 dB at 1 kHz
  - drives a 32-Ω load at 100 mW output power
Classic Bipolar vs. Rail-to-Rail Output Stage

Classic Bipolar

$$V_{sat} + V_{be}$$

$$V_{OUT}$$

$$+V_S$$

$$-V_S$$

Rail-to-Rail

$$V_{sat} = 0.2V$$

$$-V_S$$

$$R_{LOAD}$$

CMOS

$$V_{sat} = 1mV \ldots 50mV$$

$$-V_S$$

Note: W/L sets Ron

$$V_{sat} = 0 \ldots 0.2V$$

$$R_{LOAD}$$

$$V_{sat} = 1mV \ldots 50mV$$
# Classic Bipolar vs. Rail-to-Rail Output Stage

<table>
<thead>
<tr>
<th>Model</th>
<th>Technology</th>
<th>Output design</th>
<th>Supply V+ to V-</th>
<th>Op Current typ</th>
<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Output Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA827</td>
<td>JFET + Bipolar</td>
<td>PNP/ NPN Emitter Followers</td>
<td>8 – 36 V</td>
<td>4.8 mA</td>
<td>75 uV</td>
<td>0.1 uV/°C</td>
<td>3 pA</td>
<td>(V-) + 3 V, (V+) – 3 V RL = 1 kΩ, Aol &gt; 120 dB</td>
</tr>
<tr>
<td>OPA209</td>
<td>Bipolar</td>
<td>PNP/NPN Collectors</td>
<td>10 – 30 V</td>
<td>3.7 mA</td>
<td>10 uV</td>
<td>0.3 uV/°C</td>
<td>2.5 nA</td>
<td>(V-) + 0.6 V, (V+) – 0.6 V RL = 2 kΩ, Aol &gt; 94 dB</td>
</tr>
<tr>
<td>OPA340</td>
<td>LV CMOS</td>
<td>P-Drain N-Drain</td>
<td>2.5 – 5.5 V</td>
<td>750 uA</td>
<td>150 uV</td>
<td>4 uV/°C</td>
<td>0.2 pA</td>
<td>(V-) + 1 mV, (V+) – 1 m V RL = 100 kΩ, Aol &gt; 106 dB</td>
</tr>
</tbody>
</table>

- **OPA340**
  - Rail-to-rail CMOS op amp optimized for low-voltage, single-supply operation
  - Voltage Output Swing typically 1 mV from rails for $R_L = 100$ kΩ, $Aol \geq 106$ dB
  - Closest swing to rail of any PA op amp
Bipolar vs. CMOS Output Swing vs. I_{out}
Open Loop Output Impedance: $Z_o$ – Bipolar vs. CMOS

Bipolar is generally the flattest and lowest $Z_o$

CMOS $Z_o$ is often higher and not as flat as Bipolar.

Zero Drift amplifiers and microPower amplifiers often have a complex $Z_o$.

Note:

$Z_o$ is an important factor when an op amp drives capacitive loads. Accurate SPICE op amp macromodels can be used to predict behavior and stabilize op amp circuits.
Bipolar vs. CMOS Bandwidth vs. $I_q$

**BIPOLAR**

\[ g_m = \frac{q \cdot I_c}{k \cdot T} \]

\[ r_{gm} = \frac{1}{g_m} \]

\[ BW = \frac{g_m}{2 \cdot \pi C_c} = \frac{1}{2 \cdot \pi C_c \cdot r_{gm}} \]

\[ BW = \frac{q \cdot I_c}{2 \cdot \pi C_c \cdot k \cdot T} \]

**MOSFET**

\[ g_m = \sqrt{\frac{2 \cdot I_D \cdot \mu \cdot C_{ox}}{W \cdot L}} \]

\[ r_{gm} = \frac{1}{g_m} \]

\[ BW = \frac{g_m}{2 \cdot \pi C_c} = \frac{1}{2 \cdot \pi C_c \cdot r_{gm}} \]

\[ BW = \sqrt{\frac{2 \cdot I_D \cdot \mu \cdot C_{ox} \cdot W}{2 \cdot \pi C_c \cdot L}} \]

- CMOS BW increases by increasing W/L or $I_d$
- CMOS BW increases by square root of $I_d$
- Bipolar increases linearly with $I_c$
Junction Isolation vs. Dielectrically Isolated

Junction Isolation

Dielectrically Isolated
Junction Isolation vs. Dielectrically Isolated

High performance, JFET input, bipolar op amps

<table>
<thead>
<tr>
<th>Model</th>
<th>Technology</th>
<th>Rail-to-rail</th>
<th>Supply V+ to V-</th>
<th>Op Current typ</th>
<th>Offset typ</th>
<th>Offset drift typ</th>
<th>Bias Current typ</th>
<th>Voltage noise 1 kHz</th>
<th>GBW</th>
<th>Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA827</td>
<td>Junction isolation</td>
<td>No</td>
<td>8V - 36 V</td>
<td>4.8 mA</td>
<td>75 uV</td>
<td>0.1 uV/°C</td>
<td>8 pA</td>
<td>4 nV/√Hz</td>
<td>22 MHz</td>
<td>28 V/us</td>
</tr>
<tr>
<td>OPA627</td>
<td>Dielectric isolation</td>
<td>No</td>
<td>9V – 36 V</td>
<td>7 mA</td>
<td>40 uV</td>
<td>0.4 uV/°C</td>
<td>1 pA</td>
<td>5.2 nV/√Hz</td>
<td>16 MHz</td>
<td>55 V/us</td>
</tr>
</tbody>
</table>

- **OPA827** - Low-Noise, High-Precision, JFET-Input op amp
  - Precision 16-bit to 18-bit mixed signal systems, transimpedance amplifiers

- **OPA627** – “Hallmark” High-Precision JFET-Input op amp
  - lower noise, lower offset voltage, and higher speed than most JFET input op amps
  - Voltage noise performance comparable with the best bipolar-input op amps
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMOS</th>
<th>Bipolar</th>
<th>JFET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vos</strong></td>
<td>Generally Larger than bipolar. Complex trim. Inherent ≈ 5mV, Trimmed ≈ 500uV</td>
<td>Generally smaller than JFET and CMOS. Laser Trim Only. Inherent ≈ 200uV, Trimmed ≈ 20uV</td>
<td>Generally Larger than bipolar. Complex trim. Laser Trim Only. Inherent ≈ 1mV, Trimmed ≈ 100uV</td>
</tr>
<tr>
<td><strong>Ib</strong></td>
<td>Low compared with bipolar $I_b \approx 1\text{pA} @ 25C$</td>
<td>Much larger than CMOS and JFET. Can use bias current calculation. Inherent ≈ 100nA, Canceled ≈ 1nA</td>
<td>Low compared with bipolar $I_b \approx 1\text{pA} @ 25C$</td>
</tr>
<tr>
<td><strong>Ib Drift</strong></td>
<td>Doubles every 10C, diode leakage $I_{B\text{,room}} \approx 1\text{pA}, T = 25C$ $I_{B\text{,hot}} \approx 1000\text{pA}, T = 125C$</td>
<td>Small compared to room temp $I_{B\text{,room}} \approx 1\text{nA}, T = 25C$ $I_{B\text{,hot}} \approx 3\text{nA}, T = 125C$</td>
<td>Doubles every 10C, diode leakage $I_{B\text{,room}} \approx 1\text{pA}, T = 25C$ $I_{B\text{,hot}} \approx 1000\text{pA}, T = 125C$</td>
</tr>
<tr>
<td><strong>Ibos</strong></td>
<td>Large offset current that is comparable to $I_b$. Don’t use resistor to cancel effects. $I_b \approx \pm 1\text{pA}$, $I_{bos} = \pm 1\text{pA}$</td>
<td>When bias current cancellation is not used $I_{bos}$ is low relative to $I_b$. Resistor can help cancel effects. $I_b = 100\text{nA}$, $I_{bos} = \pm 1\text{nA}$</td>
<td>Large offset current that is comparable to $I_b$. Don’t use resistor to cancel effects. $I_b \approx \pm 1\text{pA}$, $I_{bos} = \pm 1\text{pA}$</td>
</tr>
<tr>
<td>Parameter</td>
<td>CMOS</td>
<td>Bipolar</td>
<td>JFET</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Broadband Noise</td>
<td>✗ Generally Larger than bipolar. Noise decreases to the square root of Id.</td>
<td>✔ Generally smaller than JFET and CMOS. Noise decreases directly with Id.</td>
<td>✗ Slightly higher than Bipolar</td>
</tr>
<tr>
<td>1/f Noise</td>
<td>✗ Generally worse than bipolar. Noise Corner &gt; 1kHz</td>
<td>✔ Generally better than CMOS. Noise Corner &lt; 10Hz</td>
<td>✔ Generally better than CMOS, but not as good as bipolar. Noise Corner &lt; 100Hz</td>
</tr>
<tr>
<td>Back-to-Back Diodes</td>
<td>✔ May or may not be required. Check Data Sheet!</td>
<td>✗ Generally required</td>
<td>✔ Not required. Check Data Sheet</td>
</tr>
<tr>
<td>Integrated Digital?</td>
<td>✔ Yes. i.e. Chopper, package trim</td>
<td>✗ No</td>
<td>✗ No</td>
</tr>
<tr>
<td>Rail to Rail Input</td>
<td>✔ Yes</td>
<td>✗ No.</td>
<td>✗ Not common. Difficult</td>
</tr>
<tr>
<td>Rail to Rail Output</td>
<td>Very close to the rail. 10mV</td>
<td>Close to the rail. 200mV</td>
<td>Same as bipolar</td>
</tr>
<tr>
<td>Output vs. Load</td>
<td>✗ Falls off quickly with load. Ron of output transistor.</td>
<td>✔ Relatively flat until you reach current limit. Vsat not related to Ron as with CMOS.</td>
<td>Same as bipolar</td>
</tr>
</tbody>
</table>
Thank you