Op Amp Technology Overview

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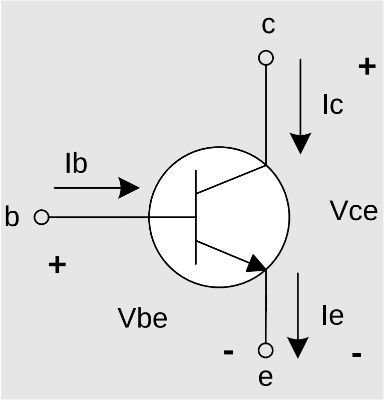
Precision Analog – Op Amps

Bipolar vs. CMOS / JFET

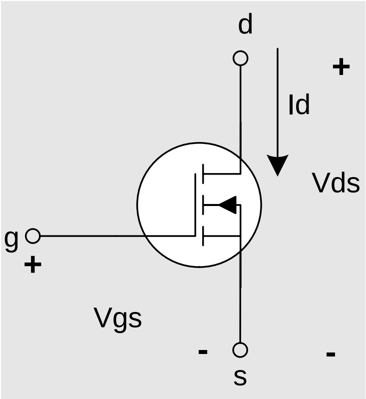
- Transistor technologies
  - Bipolar, CMOS and JFET
- Vos and Ib and Drift
  - Laser Trim, Package Trim, and Zero Drift
- Noise
  - JFET, MOSFET, and Bipolar (1/f noise)
- Input Structures
  - Rail-to-Rail, Charge Pump
  - Chopper (Zero-Drift)
    - Chopper Noise Sources
  - Input crossover distortion
  - 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)



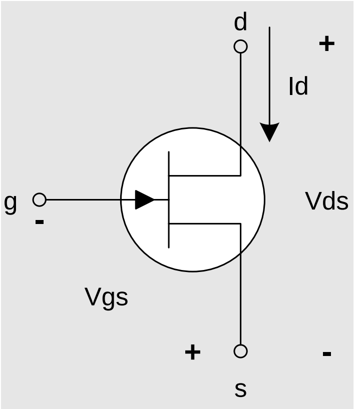
NPN **Bipolar**

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



N-Channel **CMOS**

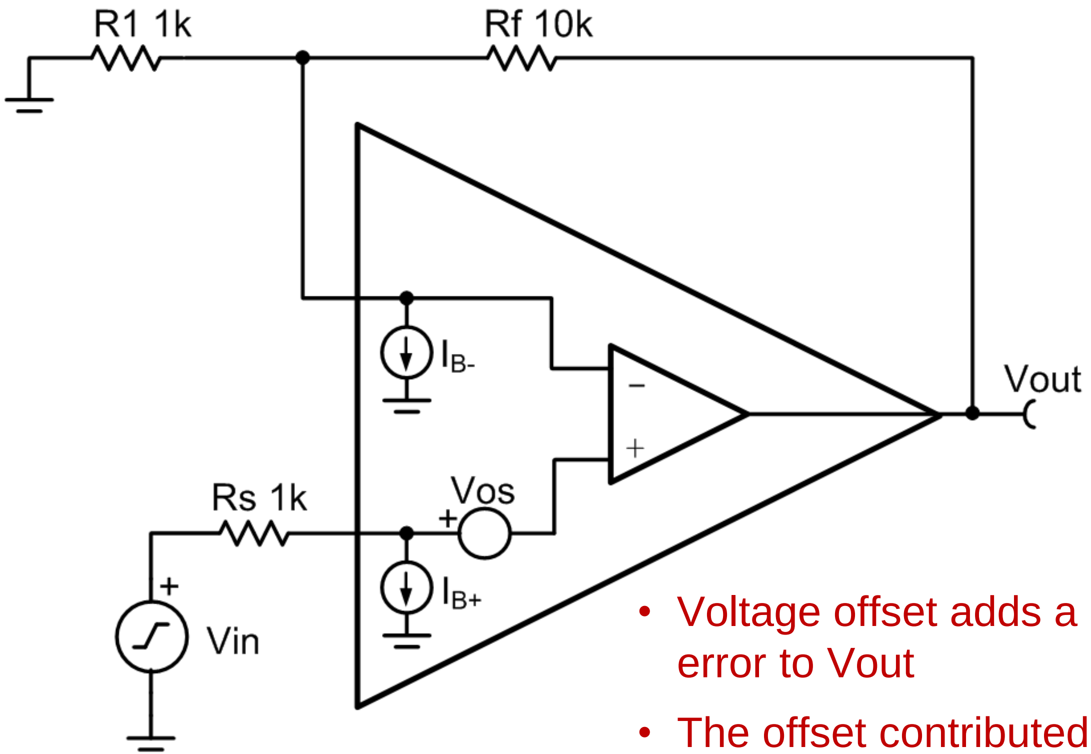
1) Voltage Controlled Device
2) “Voltage Controlled Resistor”
3) Vgs > 2V controls Rds_on
4) Vgs=0V turns MOSFET off
5) Gate is op amp +/- input
6) Very Low Op Amp input current



N-Channel **JFET**

1) Voltage Controlled Device
2) “Voltage Controlled Resistor”
3) 0V< Vgs < -2V controls Rds_on
4) Vgs < -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

$$R_{eq} = \frac{R_f \cdot R_1}{R_f + R_1}$$

$$G_n = \frac{R_f}{R_1} + 1$$

$$V_{o\_vos} = V_{os} \cdot G_n$$

$$V_{o_{Ib}+} = I_b \cdot R_s \cdot G_n$$

$$V_{o_{Ib}-} = I_b \cdot R_{eq} \cdot G_n$$

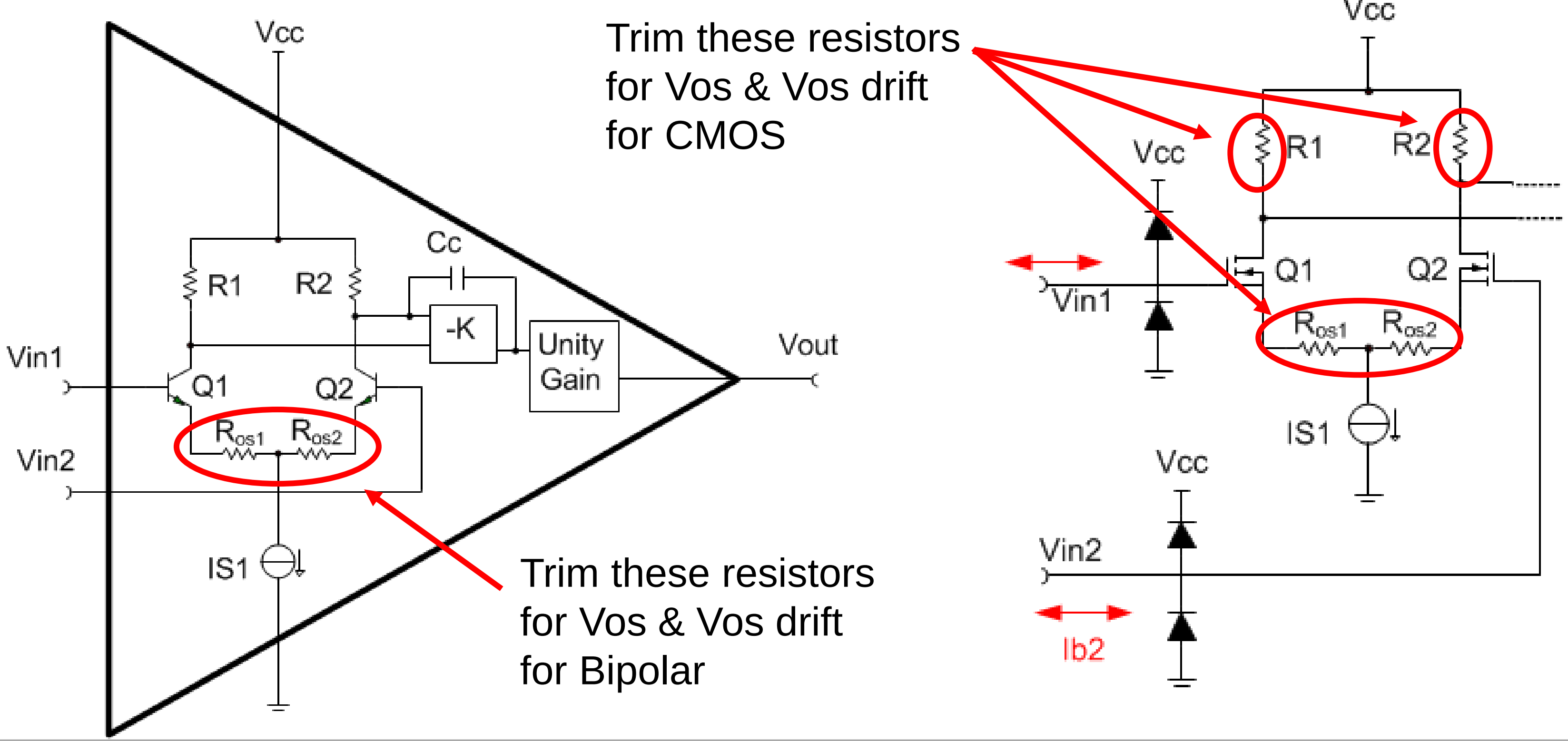
$$V_{o\_os\_Ib} = V_{o\_vos} + V_{o_{Ib}+} + V_{o_{Ib}-}$$

TEXAS INSTRUMENTS

What’s inside the Amplifier – Bipolar vs. CMOS

Bipolar input op amp

CMOS input op amp

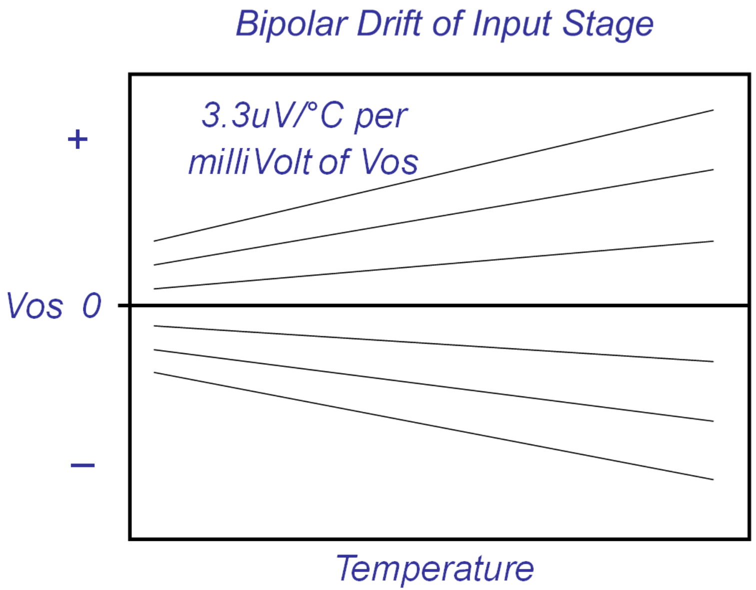


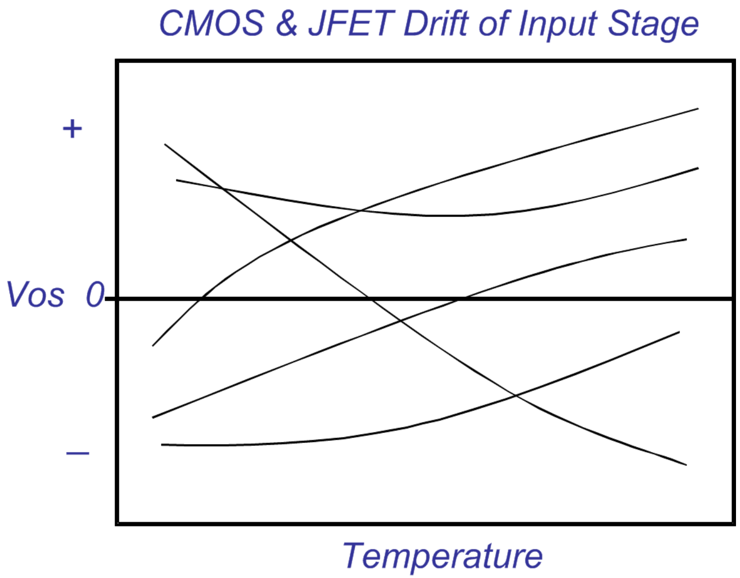
Bipolar and CMOS

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

- 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_{Load} drive capability

Inherent Drift of Bipolar vs. CMOS

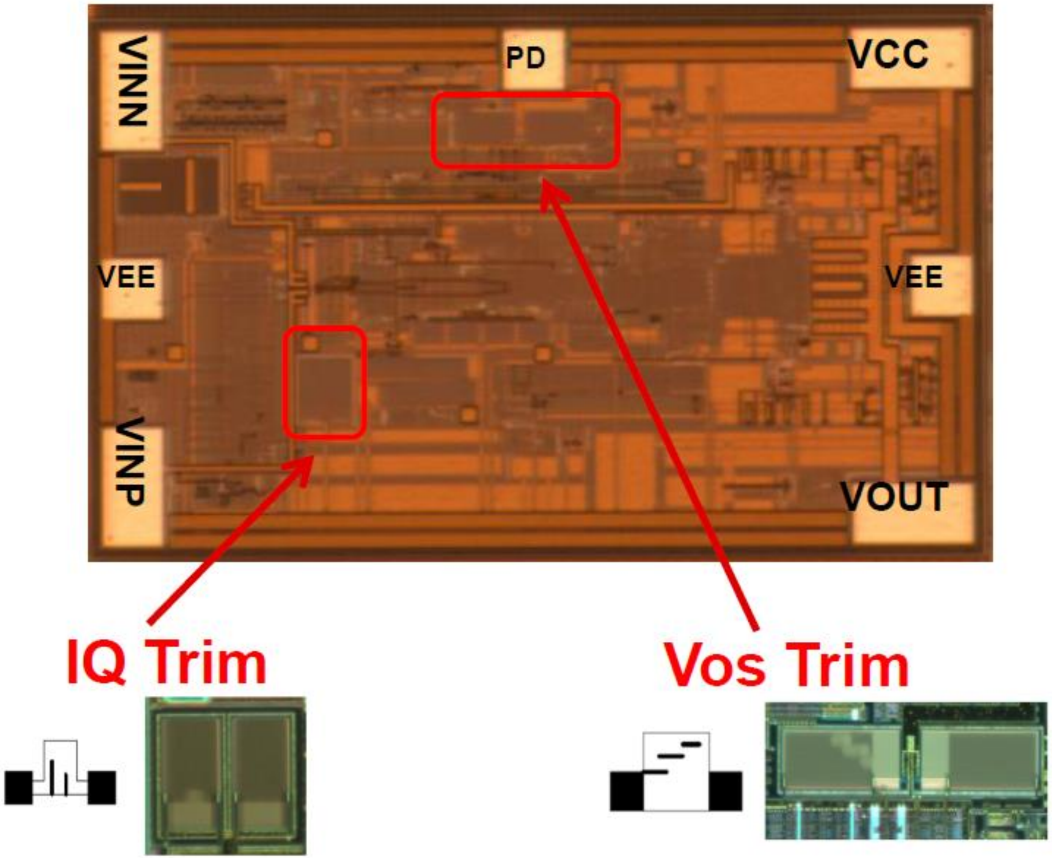




- Drift is proportional to offset
- When Vos trimmed to zero, drift is near zero.
- Simple one step trim: just trim offset

- Frequently more curvature than bipolar
- When Vos 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

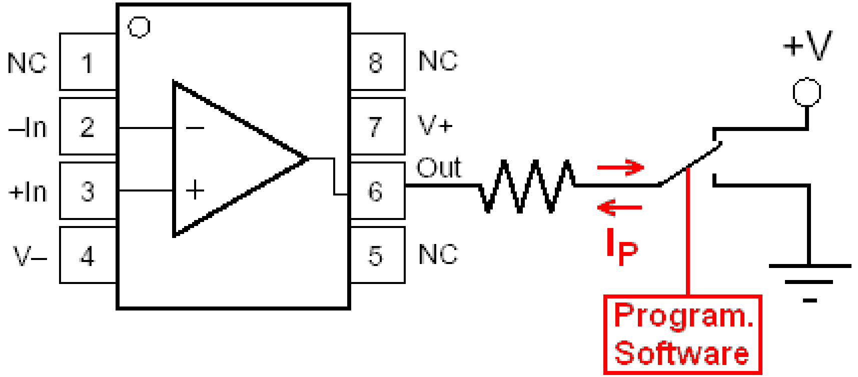
Bipolar vs. CMOS

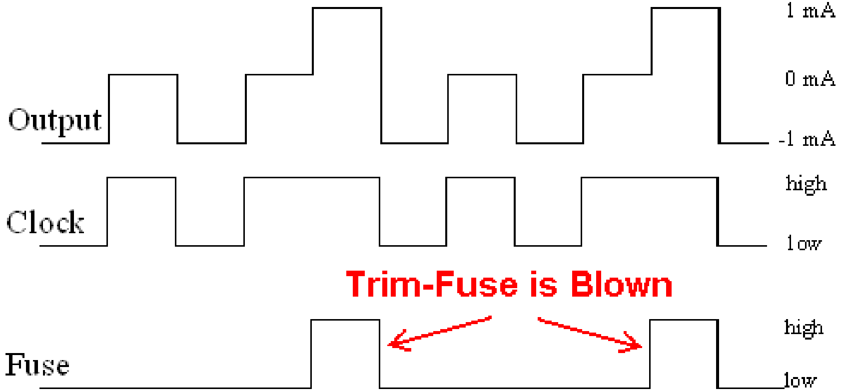
Op amps that utilize thin-film resistor laser trimming for improved offset and drift

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

- 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, RRI/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

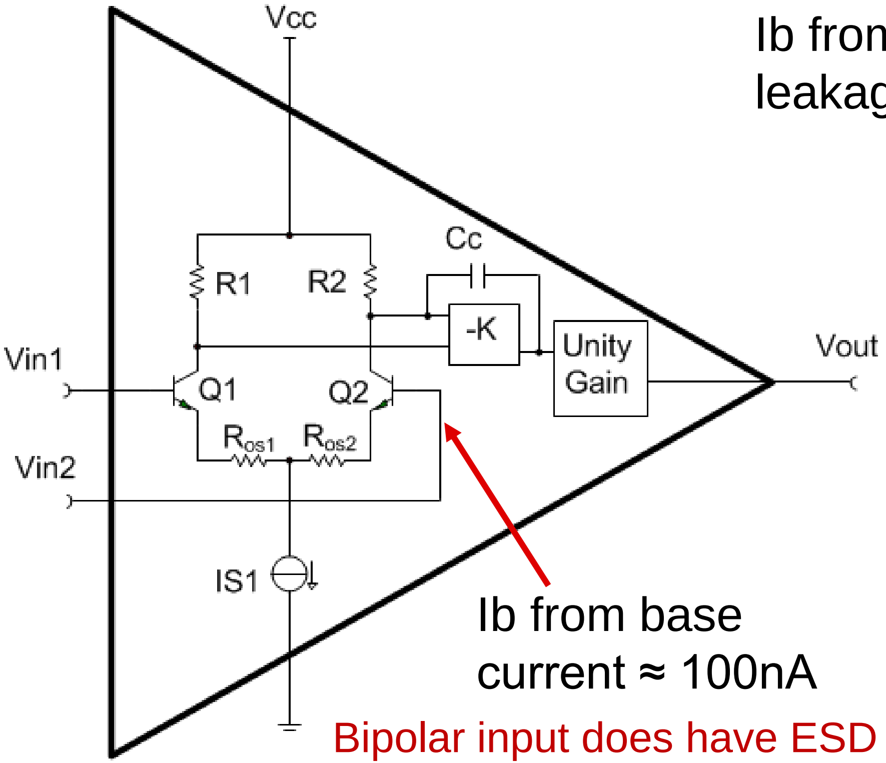
e-trim™

Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA376	LV CMOS	RRIO	2.2 – 5.5 V	760 uA	5 uV	0.26 uV/°C	0.2 pA	7.5 nV/√Hz	5.5 MHz	2 V/us
OPA192	HV CMOS	RRIO	8 – 36 V	1 mA	5 uV	0.1 uV/°C	5 pA	5.5 nV/√Hz	10 MHz	20 V/us

- 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

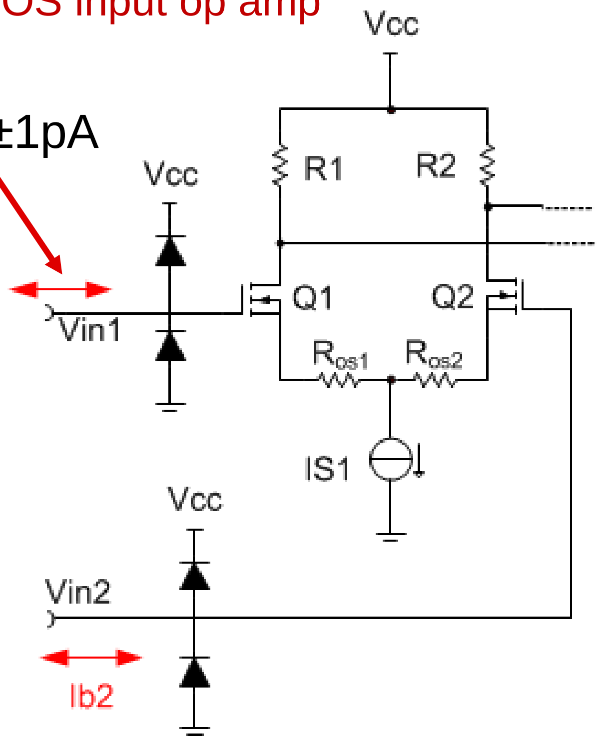
Bipolar input op amp



Ib from base current ≈ 100nA

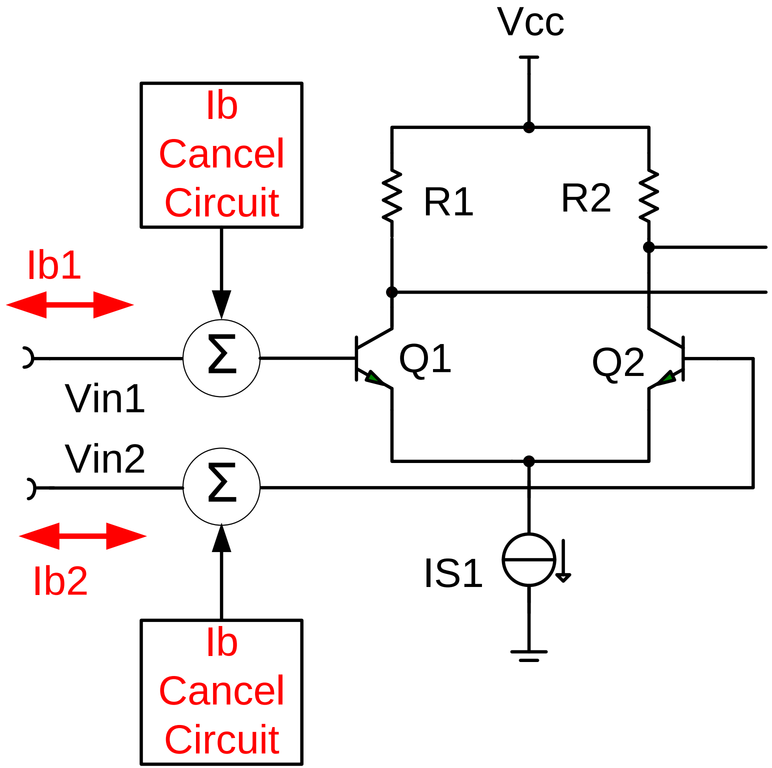
CMOS input op amp

Ib from diode leakage Ib ≈ ±1pA



Bipolar input does have ESD cells, but Ib >> I_{leak}

Bipolar - Bias Current Cancellation



Bipolar IB	Typical
Uncancelled	100nA
Cancelled	1nA

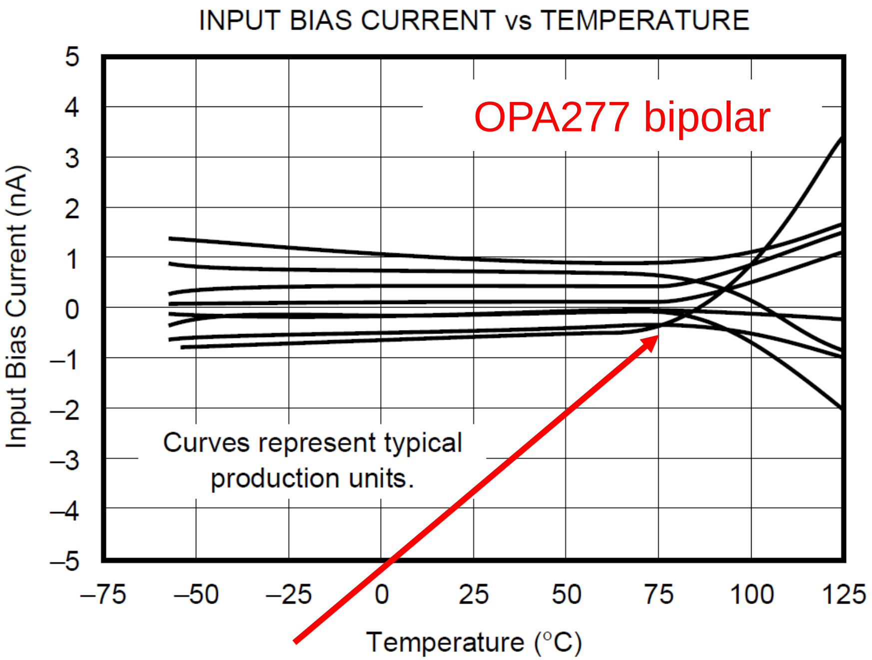
Bipolar - Bias Current Cancellation

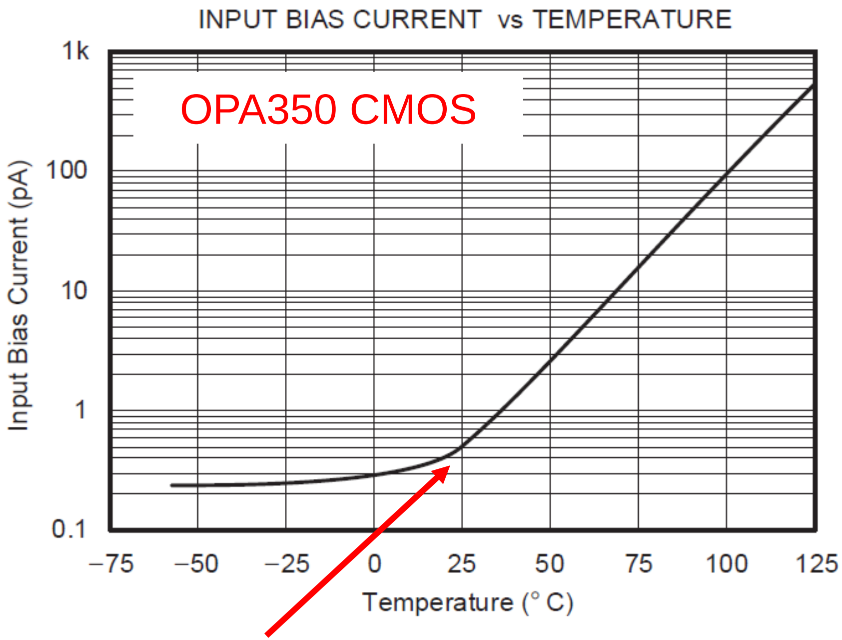
Cancellation vs non-cancellation

Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA209	Bipolar with Ib cancel	RRO	4.5 - 36 V	2.2 mA	35 uV	0.05 uV/°C	1 nA typ 4.5 nA max	2.2 nV/√Hz	18 MHz	6.4 V/us
OPA211	Bipolar w/o Ib cancel	RRO	4.5 - 36 V	3.6 mA	60 uV	0.35 uV/°C	60 nA typ 175 nA max	1.1 nV/√Hz	45 MHz	27 V/us

- 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)

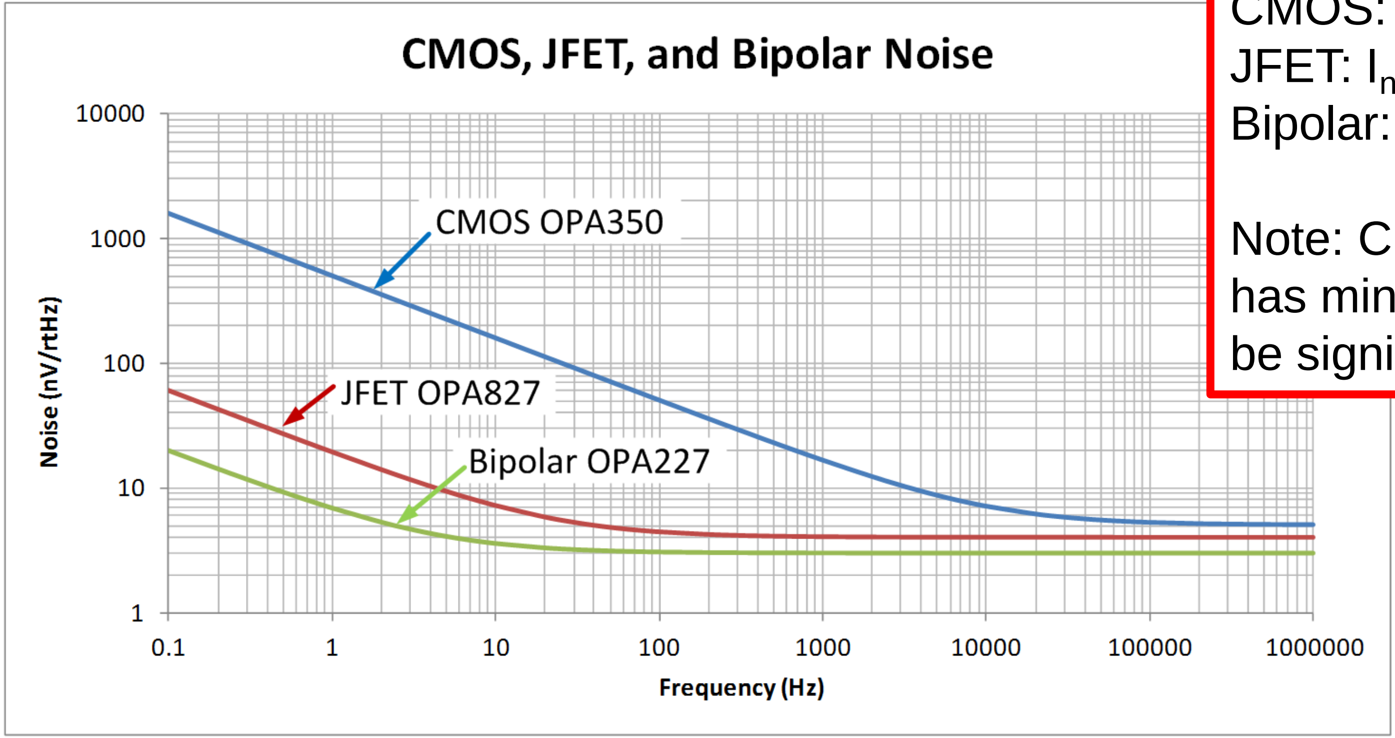




<u>Bipolar amplifier:</u>
In this case you see a dramatic increase in bias current at 75 °C.

<u>CMOS amplifier:</u>
In this case you see a dramatic increase in bias current at 25 °C. Note the logarithmic graph, which doubles every 10 °C.

JFET, Bipolar, and CMOS Noise



CMOS: I_{n_350} = 4fA/rtHz
JFET: I_{n_827} = 2.2fA/rtHz
Bipolar: I_{n_277} = 200fA/rtHz

Note: CMOS current noise has minimal 1/f, but it may be significant in bipolar

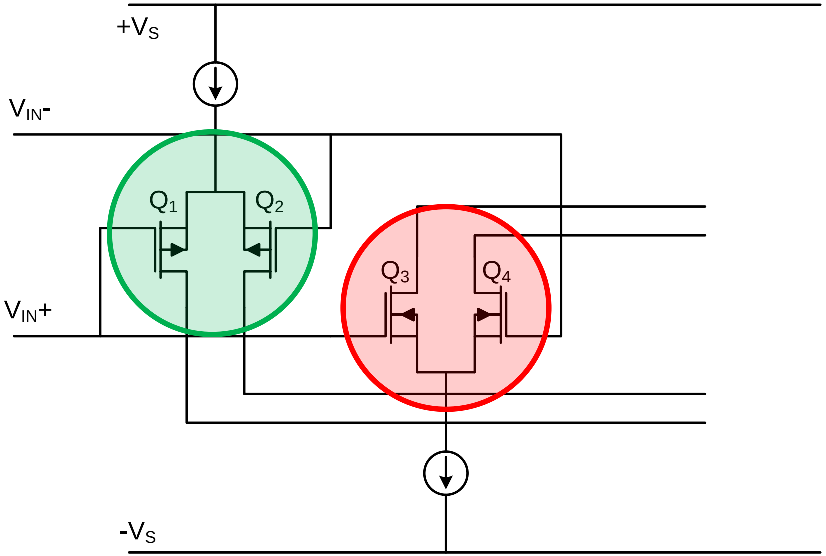
JFET, Bipolar, and CMOS Noise

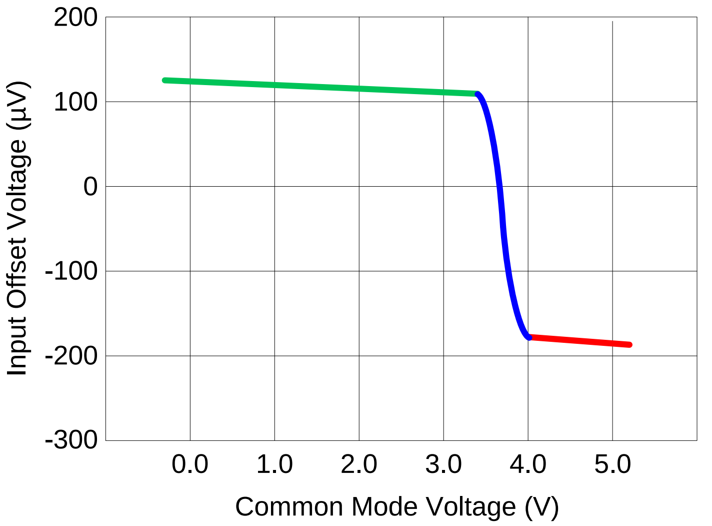
Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA827	JFET + Bipolar	No	8 – 36 V	4.8 mA	75 uV	0.1 uV/°C	3 pA	4 nV/√Hz	22 MHz	28 V/us
OPA227	Bipolar	No	10 – 36 V	3.7 mA	10 uV	0.3 uV/°C	2.5 nA	3 nV/√Hz	8 MHz	2.3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

- 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_{Load} drive capability

OPA703 Complementary CMOS – Rail-to-Rail

PARAMETER		CONDITION	MIN	TYP	MAX	UNITS
INPUT VOLTAGE RANGE						
Common-Mode Voltage Range	V_{CM}		(V–) – 0.3		(V+) + 0.3	V
Common-Mode Rejection Ratio	CMRR	$V_S = \pm 5V$, $(V-) - 0.3V < V_{CM} < (V+) + 0.3V$	70	90		dB
over Temperature		$\mathbf{V_S = \pm 5V, (V-) < V_{CM} < (V+)}$	**68**			**dB**
		$V_S = \pm 5V$, $(V-) - 0.3V < V_{CM} < (V+) - 2V$	80	96		dB
over Temperature		$\mathbf{V_S = \pm 5V, (V-) < V_{CM} < (V+) - 2V}$	**74**			**dB**

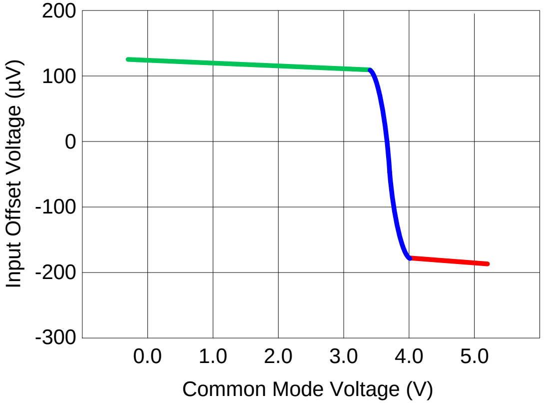




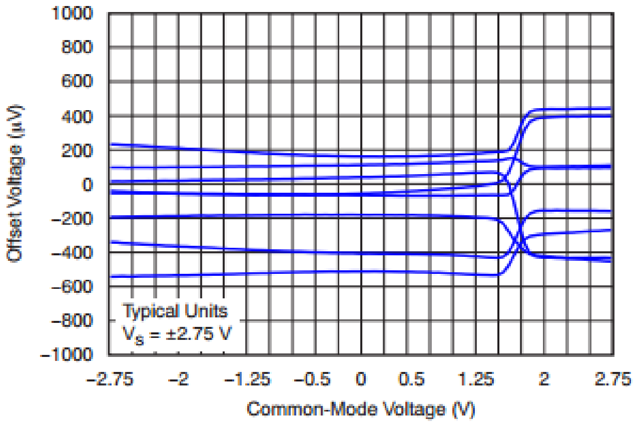
Complementary CMOS – Rail-to-Rail

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

Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA703	12 V CMOS	RRIO	4 - 12 V	160 uA	35 uV	4 uV/°C	1 pA	45 nV/√Hz	1 MHz	0.6 V/us
OPA314	LV CMOS	RRIO	1.8 – 5.5 V	150 uA	60 uV	1 uV/°C	0.4 pA	14 nV/√Hz	2.7 MHz	1.5 V/us

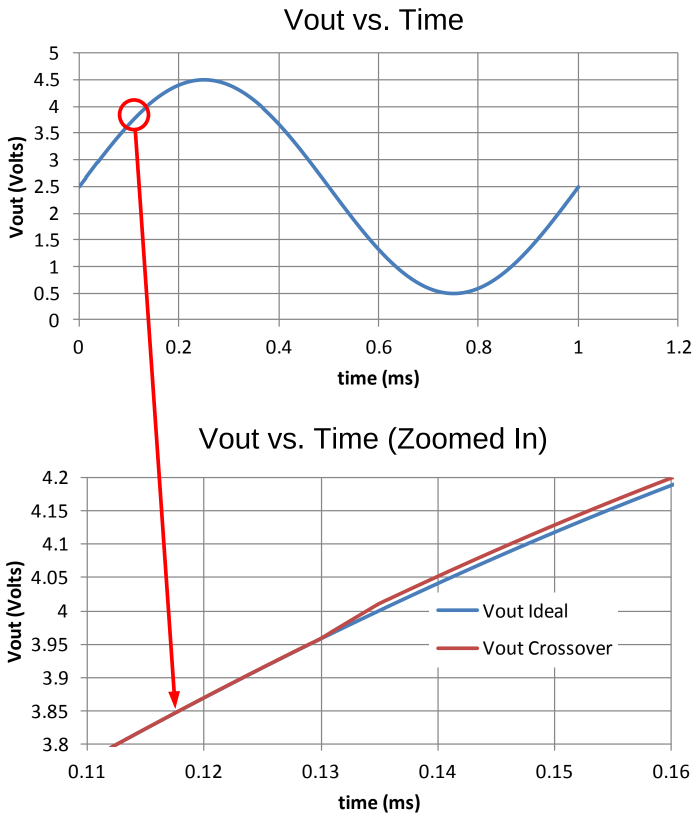


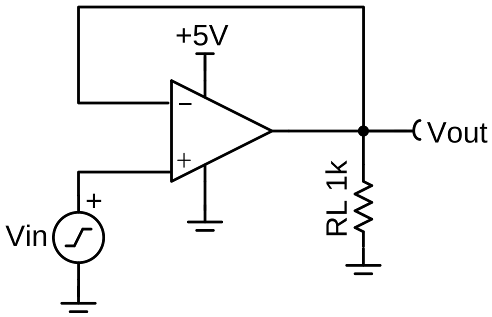
OPA703 0 to +5 V input, V_S ±5 V

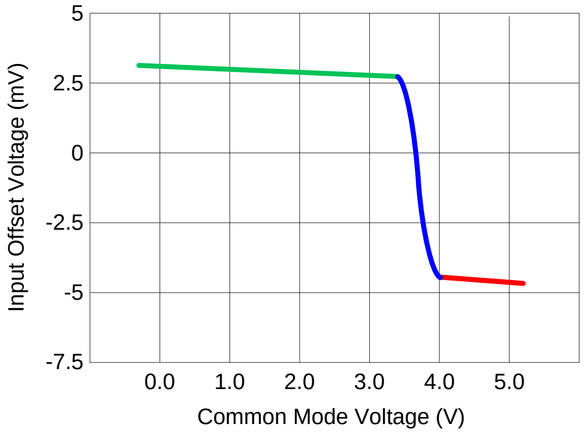


OPA314 ±2.75 V input, V_S ±2.75 V

Input Crossover Distortion

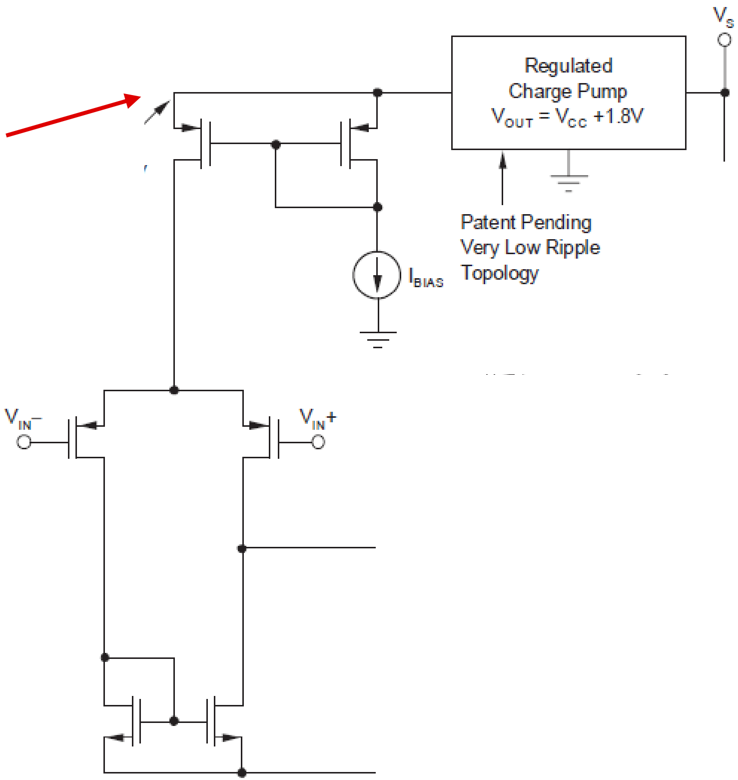






OPA365 MOSFET Charge Pump – Rail-to-Rail

$V_{OUT} = +V_S + 1.8V$



- Uses charge pump to raise V+ rail and overcome Vsat + Vgs 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

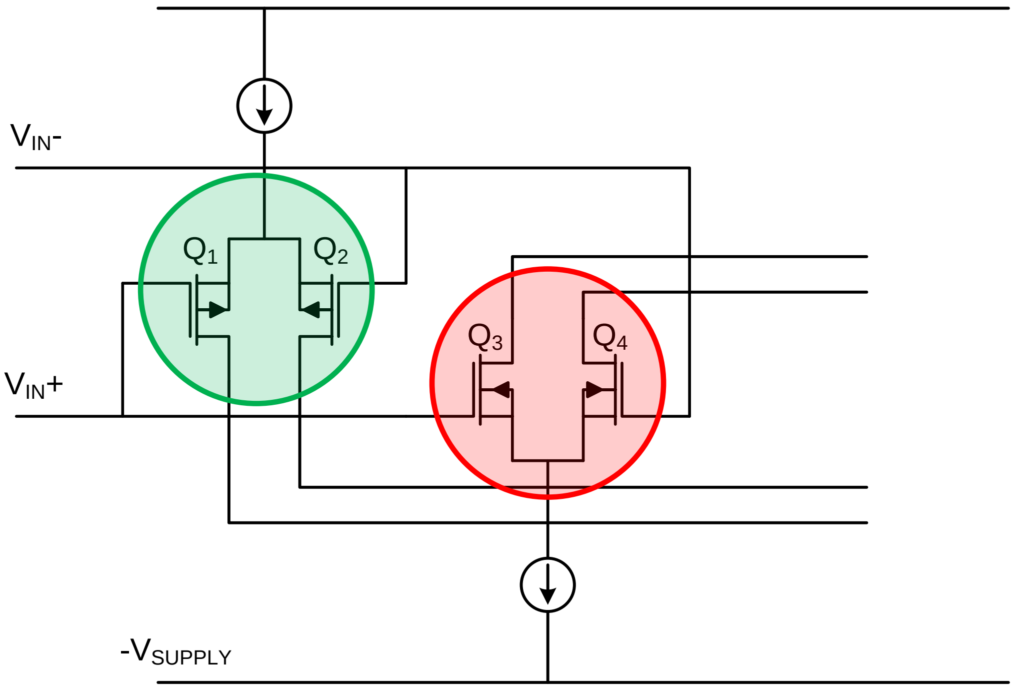
Eliminates input stage crossover distortion

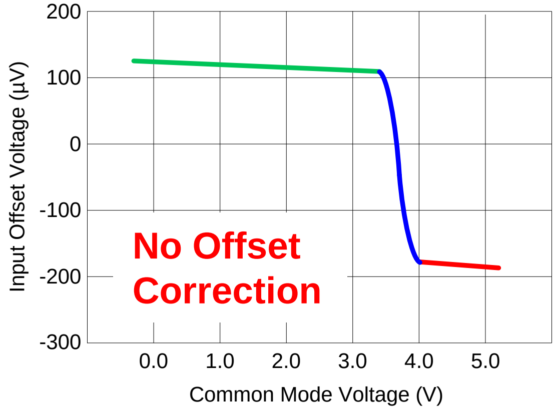
Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA365	LV CMOS	RRIO	2.2 – 5.5 V	4.6 mA	100 uV	1 uV/°C	0.2 pA	12 nV/√Hz	50 MHz	25 V/us
OPA322	LV CMOS	RRIO	1.8 – 5.5 V	1.5 mA	500 uV	1.5 uV/°C	0.2 pA	8.5 nV/√Hz	20 MHz	10 V/us

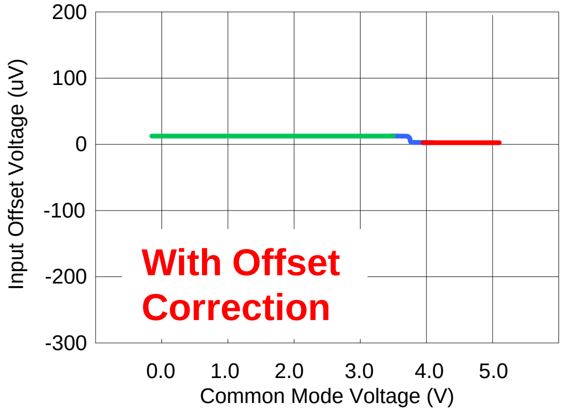
- OPA365 – Wide bandwidth, Low-Distortion, High CMRR
  - High performance optimized for low voltage, single-supply applications
- OPA322 – Wide bandwidth, Low-Noise, Low current
  - Optimized for low noise and wide bandwidth while requiring low quiescent current

Chopper and Zero Drift MOSFET – Rail-to-Rail

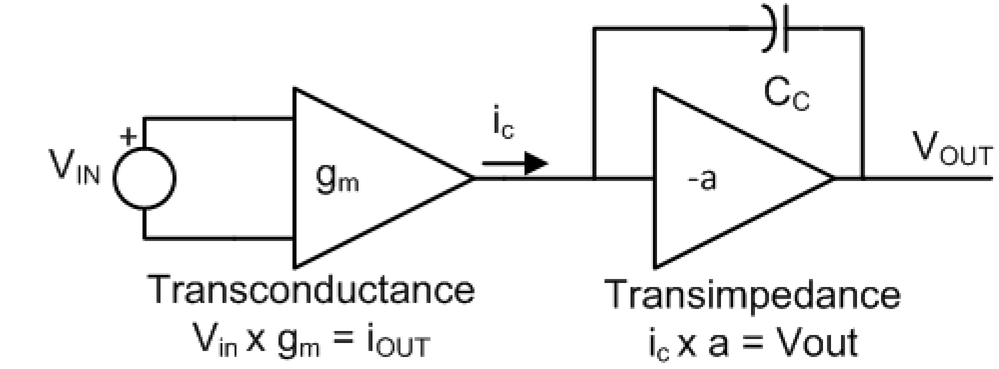
“Chopper” and “Zero-Drift” CMOS Op Amps use complementary input P-ch/ N-ch concept with Digital Calibration for Offset Correction



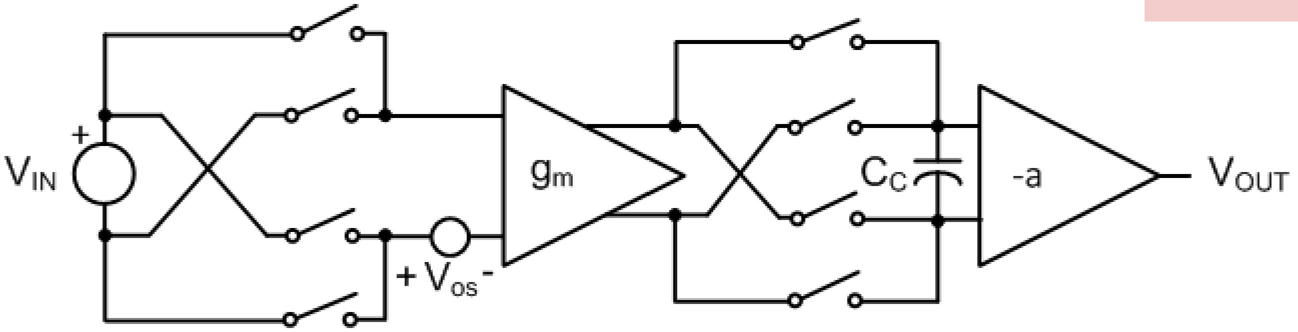




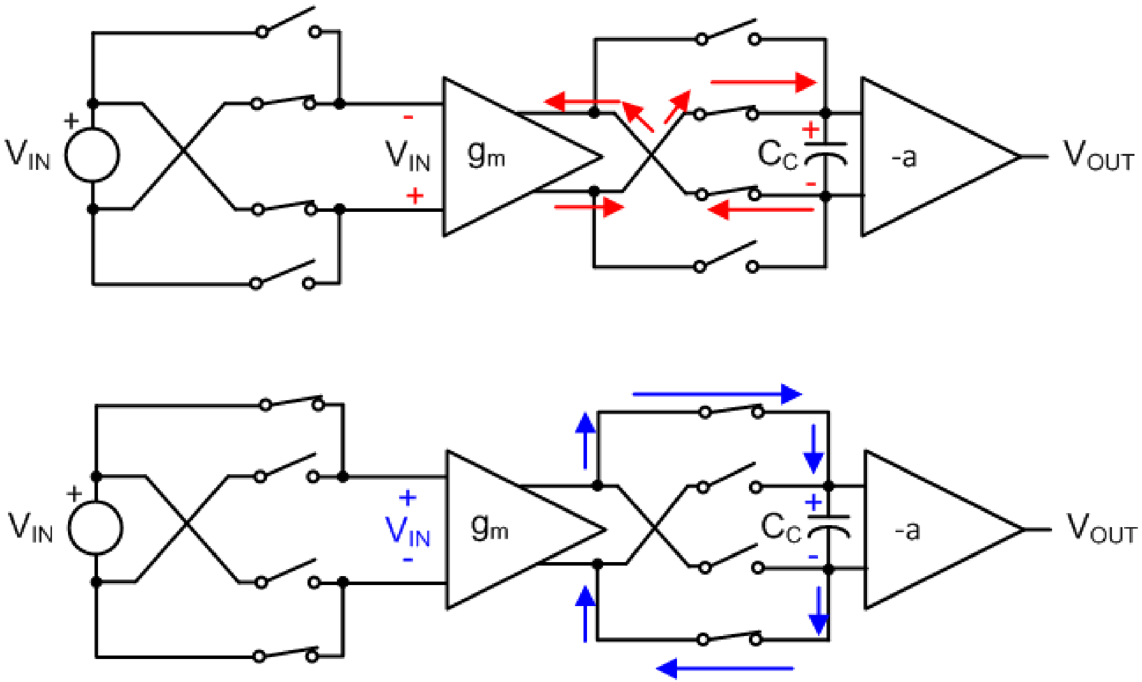
Comparing Common Architectures vs. Chopper



CMOS Vos/drift	Typ Vos (uV)	Typ Drift (uV/C)
Uncorrected	1000	5
Zero Drift (chopper)	10	0.05
Package Trim	10	0.5

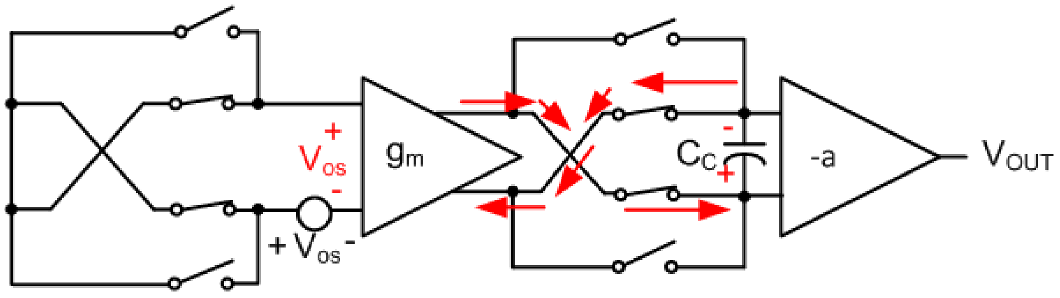


Chopper Amplifying Vin

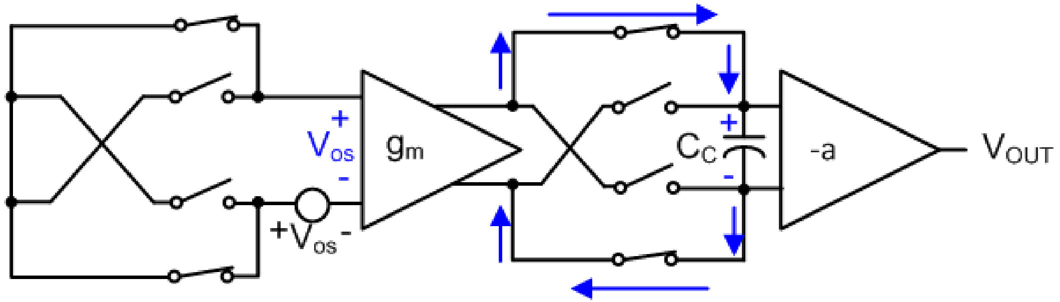


- Vin inverted at the input and output every other calibration cycle
- Overall signal path doesn't see an inversion

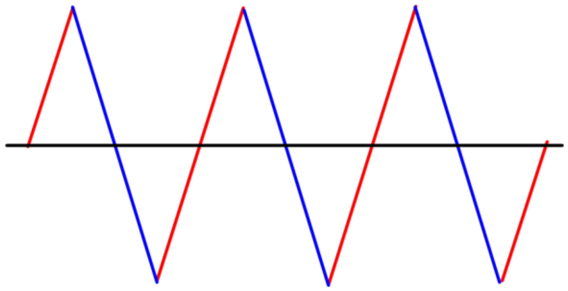
Chopper Amplifying Vos



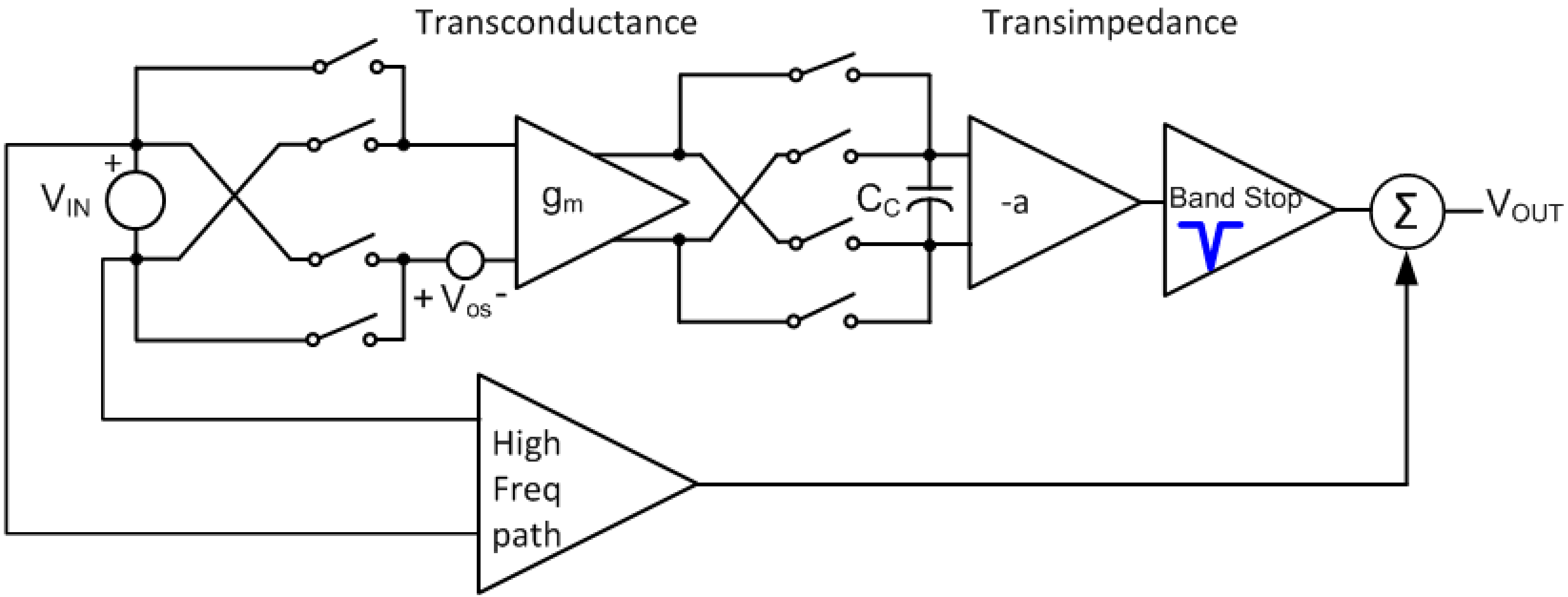
- Vos only inverted at output every other calibration cycle
- Offset translates to triangle wave
- Offset average is zero
- Sync Filter eliminates triangle wave



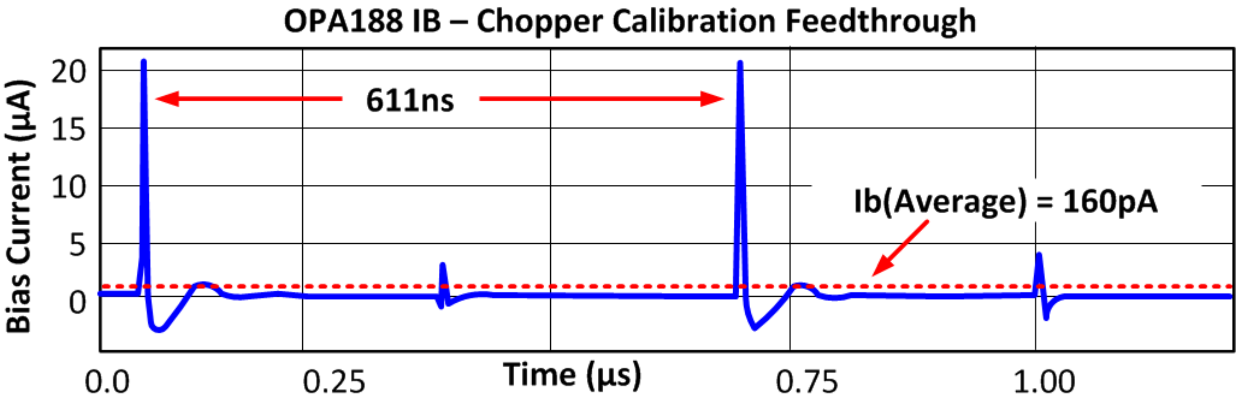
f = 125kHz on OPA333
Average = 0
Slope = $(Vos \cdot g_m)/C_c$

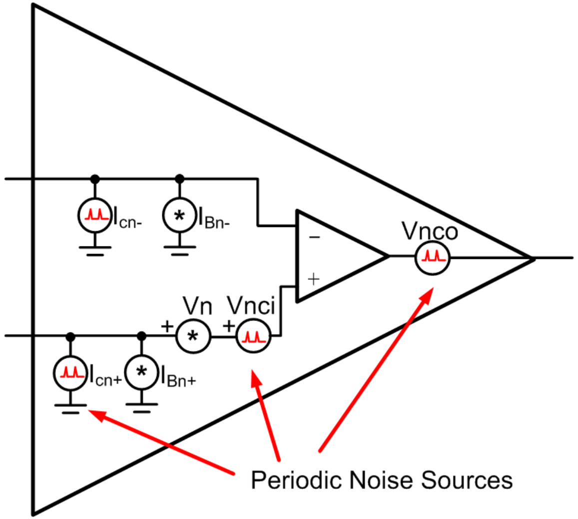


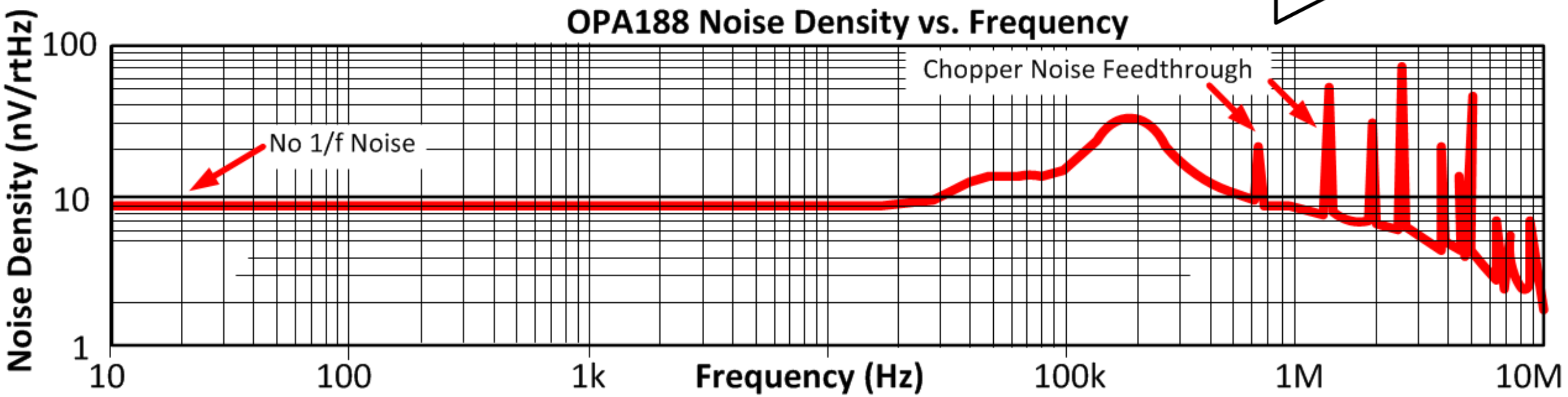
Chopper: A more complete diagram



Chopper Noise Sources and Ib







Chopper Op Amps

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

Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA333	LV CMOS	RRIO	1.8 – 5.5 V	17 uA	2 uV	0.02 uV/°C	70 pA	55 nV/√Hz	350 kHz	0.16 V/us
OPA188	HV CMOS	RRO	4- 36 V	425 uA	6 uV	0.03 uV/°C	160 pA	8.8 nV/√Hz	2 MHz	0.8 V/us

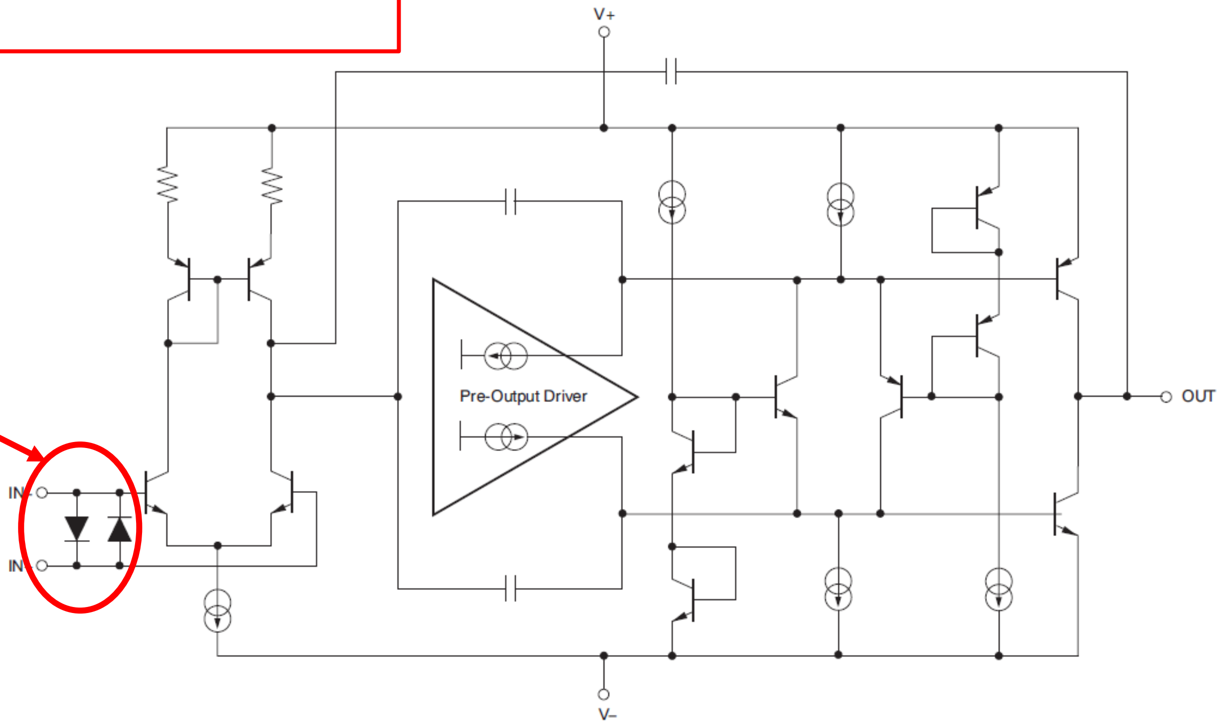
- OPA333 - 1.8 V, Precision, microPower
  - Provides excellent CMRR without the crossover associated with traditional complementary input stages
- OPA2188 – 36 V, Precision, Low-Noise, Rail-to-Rail Output
  - Offers very low offset and drift with high CMRR, PSRR, and AOL performance

Input Stage Back-to-Back Diodes

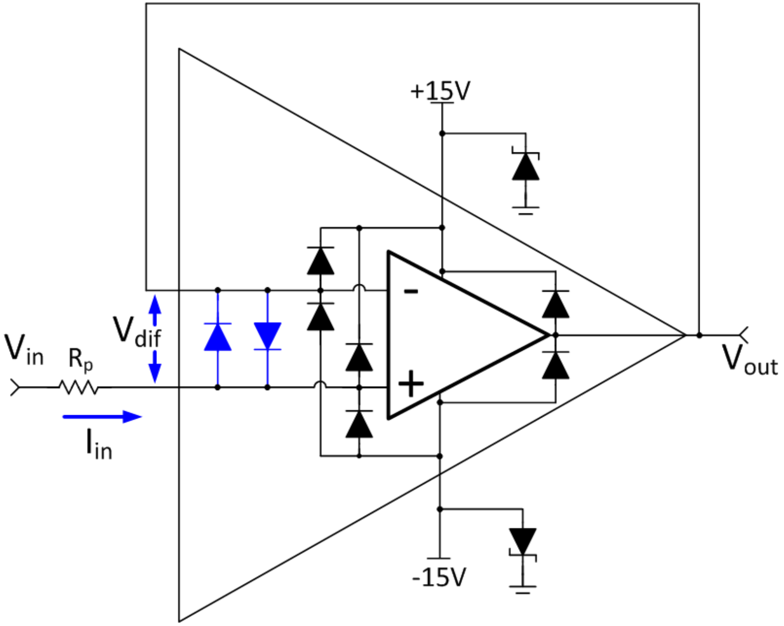
CMOS: May not be needed, Check Data Sheet.
JFET: May not be needed, Check Data Sheet.
Bipolar: Generally Required.

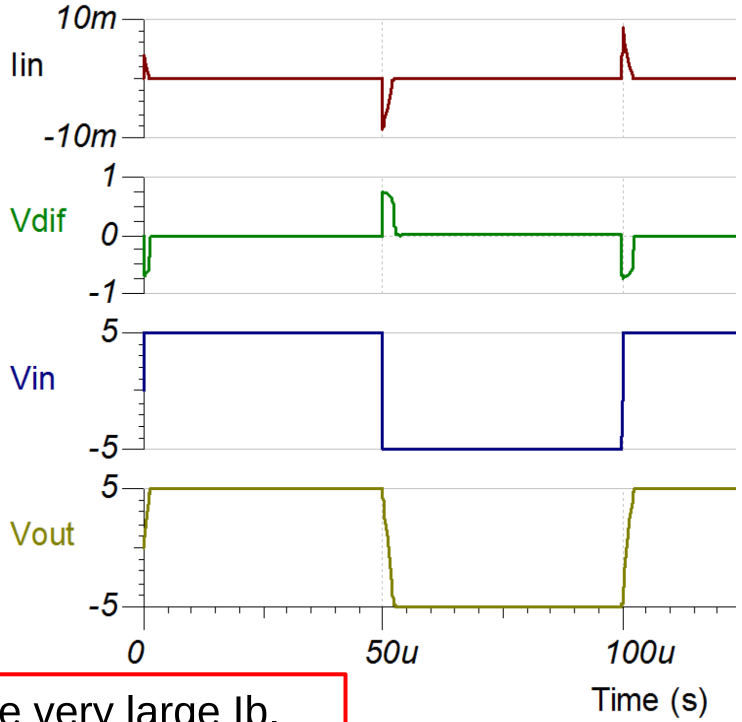
These diodes prevent overstress damage on input base to emitter junctions.

- Diodes can cause problems in multiplexed applications
- See TIPD151 for details



Input Stage Back-to-Back Diodes





The diodes can turn on during slewing and cause very large Ib.
Can be a significant problem in Mux applications (TIPD151).

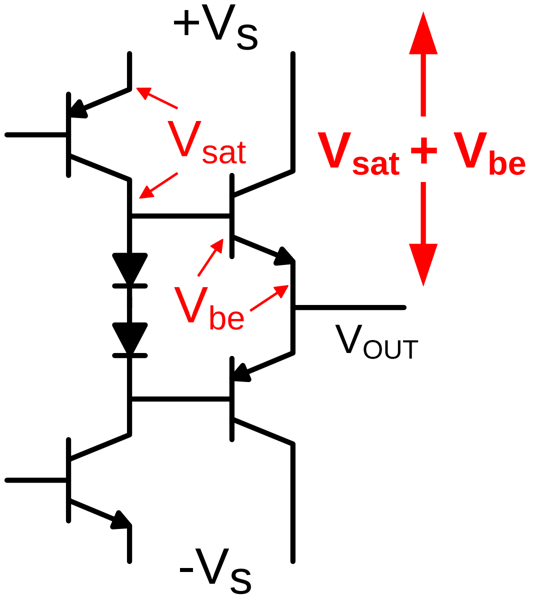
Input Stage Back-to-Back Diodes

Op amps with differential input over-voltage protection

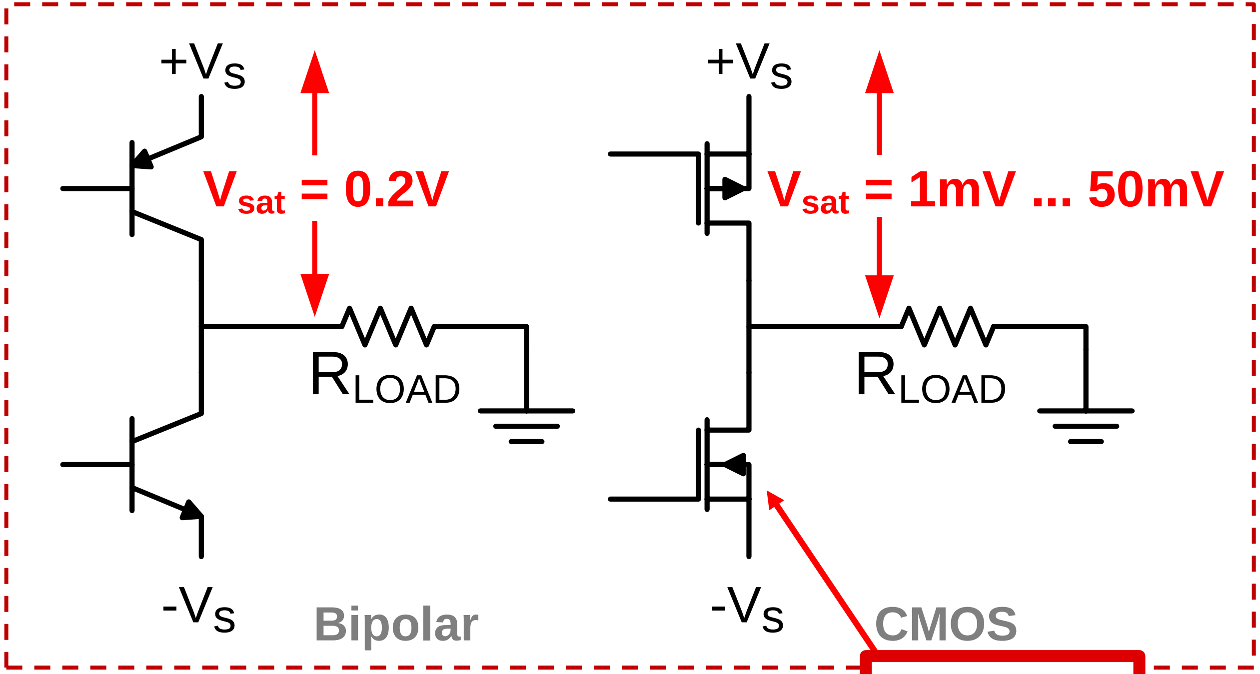
Model	Tech-nology	Rail-to-rail	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Voltage noise 1 kHz	GBW	Slew rate
OPA171	HV CMOS	RRO	2.7 - 36 V	475 uA	250 uV	0.3 uV/°C	8 pA	14 nV/√Hz	3 MHz	1.5 V/us
OPA1622	Bipolar	No	4 – 36 V	2.6 mA	100 uV	0.5 uV/°C	1.2 uA	2.8 nV/√Hz	8 MHz	10 V/us

- 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



Rail-to-Rail

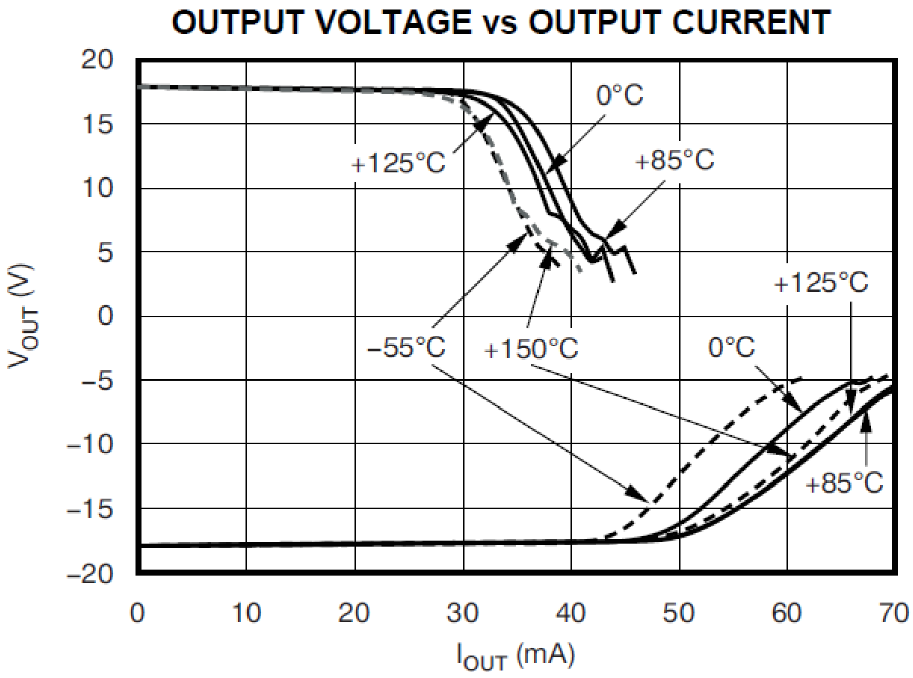
Note: W/L sets Ron

Classic Bipolar vs. Rail-to-Rail Output Stage

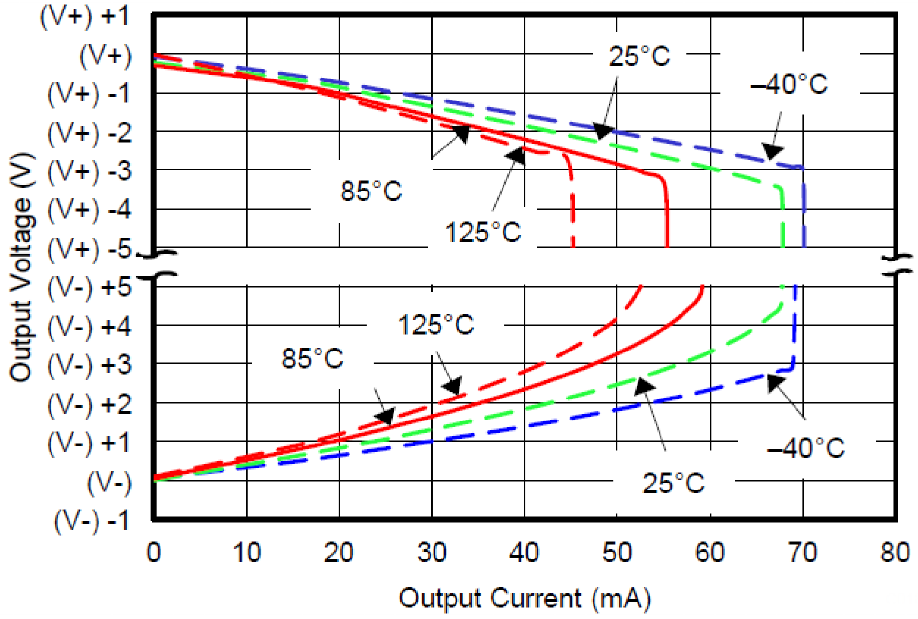
Model	Tech-nology	Output design	Supply V+ to V-	Op Current typ	Offset typ	Offset drift typ	Bias Current typ	Output Swing
OPA827	JFET + Bipolar	PNP/ NPN Emitter Followers	8 – 36 V	4.8 mA	75 uV	0.1 uV/°C	3 pA	(V-) + 3 V, (V+) – 3 V RL = 1 kΩ, Aol > 120 dB
OPA209	Bipolar	PNP/NPN Collectors	10 – 30 V	3.7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

- 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 ≥ 106 dB
  - Closest swing to rail of any PA op amp

Bipolar vs. CMOS Output Swing vs. Iout

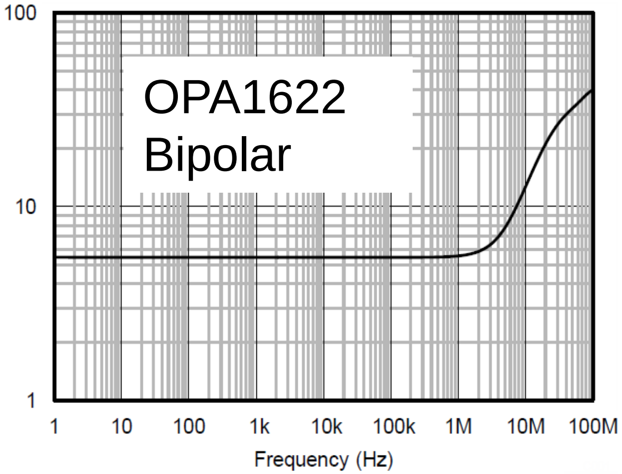


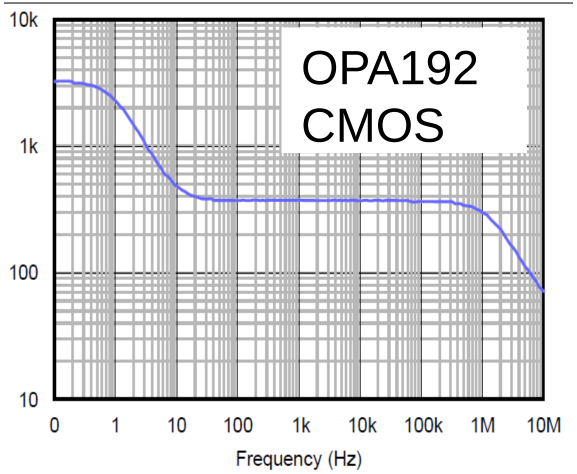
Bipolar

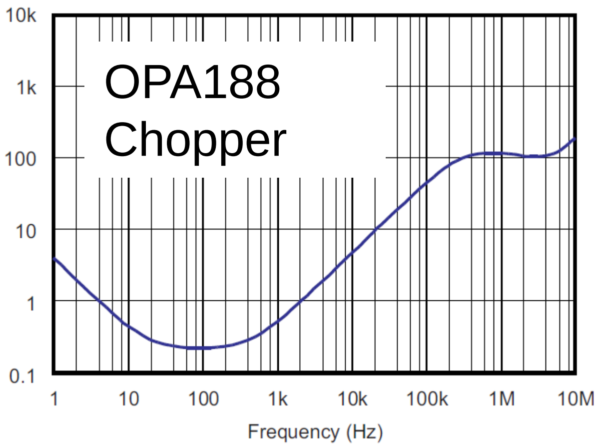


CMOS

Open Loop Output Impedance: Zo – Bipolar vs. CMOS







Bipolar is generally the flattest and lowest Zo

CMOS Zo is often higher and not as flat as Bipolar.

Zero Drift amplifiers and microPower amplifiers often have a complex Zo.

Note:
Zo 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. Iq

BIPOLAR

$$g_m = \frac{q \cdot I_c}{k \cdot T}$$

$$r_{gm} = \frac{1}{g_m}$$

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

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

- CMOS BW increases by increasing W/L or Id
- CMOS BW increases by square root of Id
- Bipolar increases linearly with Ic

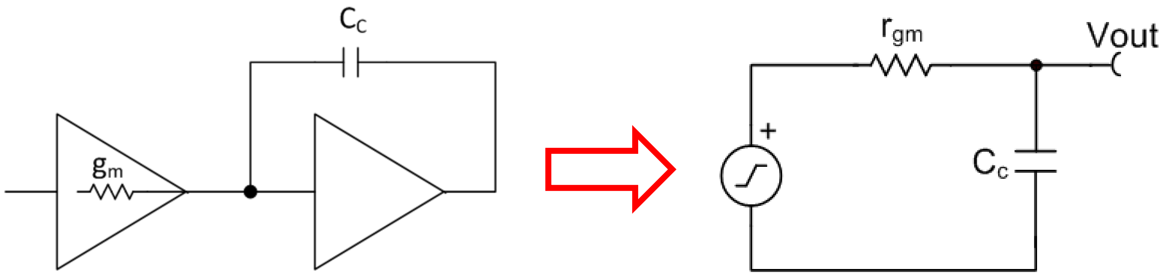
MOSFET

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

$$r_{gm} = \frac{1}{g_m}$$

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

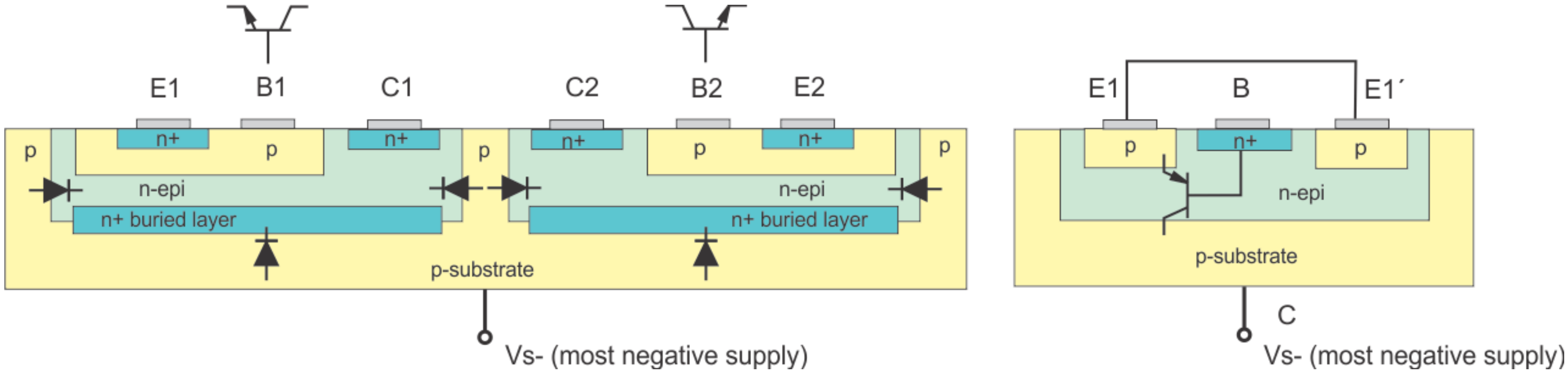
$$BW = \frac{\sqrt{2 \cdot I_D \cdot \mu \cdot C_{ox} \cdot \frac{W}{L}}}{2 \cdot \pi \cdot C_c}$$



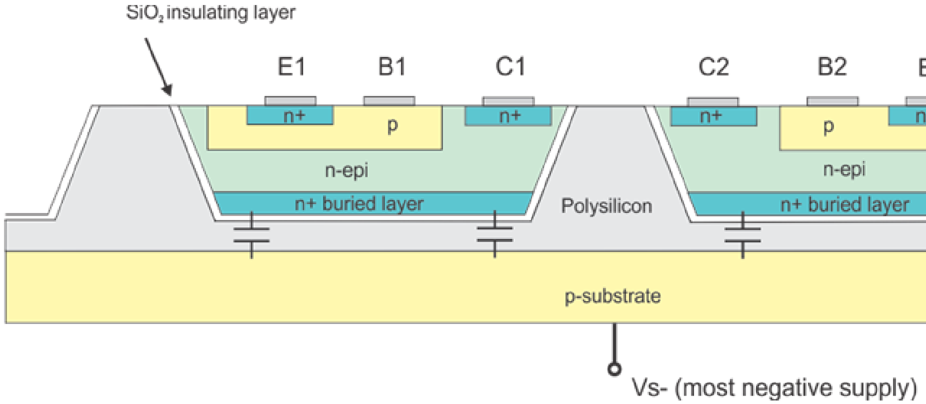
$$BW = \frac{g_m}{2 \cdot \pi \cdot C_c} = \frac{1}{2 \cdot \pi \cdot C_c \cdot r_{gm}}$$

Junction Isolation vs. Dielectrically Isolated

Junction Isolation



Dielectrically Isolated



Junction Isolation vs. Dielectrically Isolated

High performance, JFET input, bipolar op amps

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

- 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

Summary CMOS vs. Bipolar vs. JFET

Parameter	CMOS	Bipolar	JFET
Vos	☒ Generally Larger than bipolar. Complex trim. Inherent ≈ 5mV, Trimmed ≈ 500uV ☑ Can use zero drift, and package trim.	☑ Generally smaller than JFET and CMOS. Laser Trim Only. Inherent ≈ 200uV, Trimmed ≈ 20uV	☒ Generally Larger than bipolar. Complex trim. Laser Trim Only. Inherent ≈ 1mV, Trimmed ≈ 100uV
Vos Drift	☒ Generally Larger than bipolar. Complex trim. ☑ Very good if using chopper.	☑ Inherently linear and easer to trim. Laser Trim Only.	☒ Generally Larger than bipolar. Complex trim. Laser Trim Only.
Ib	☑ Low compared with bipolar Ib ≈ 1pA @ 25C	☒ Much larger than CMOS and JFET. Can use bias current calculation. Inherent ≈ 100nA, Canceled ≈ 1nA	☑ Low compared with bipolar Ib ≈ 1pA @ 25C
Ib Drift	☒ Doubles every 10C, diode leakage I_{B_room} ≈ 1pA , T = 25C I_{B_hot} ≈ 1000pA , T = 125C	☑ Small compared to room temp I_{B_room} ≈ 1nA , T = 25C I_{B_hot} ≈ 3nA , T = 125C	☒ Doubles every 10C, diode leakage I_{B_room} ≈ 1pA , T = 25C I_{B_hot} ≈ 1000pA , T = 125C
Ibos	☒ Large offset current that is comparable to Ib. Don't use resistor to cancel effects. Ib ≈ ±1pA, Ibos = ±1pA	☑ When bias current cancellation is not used Ibos is low relative to Ib. Resistor can help cancel effects. Ib = 100nA, Ibos = ±1nA ☑ When bias current cancellation is used Ibos is comparable to Ib. Don't use resistor to cancel effects. Ib = ±1nA, Ibos = ±1nA	☒ Large offset current that is comparable to Ib. Don't use resistor to cancel effects. Ib ≈ ±1pA, Ibos = ±1pA

Summary CMOS vs. Bipolar vs. JFET

Parameter	CMOS	Bipolar	JFET
Broadband Noise	☒ Generally Larger than bipolar. Noise decreases to the square root of Id.	☑ Generally smaller than JFET and CMOS. Noise decreases directly with Id.	☒ Slightly higher than Bipolar
1/f Noise	☒ Generally worse than bipolar. Noise Corner > 1kHz	☑ Generally better than CMOS. Noise Corner < 10Hz	☑ Generally better than CMOS, but not as good as bipolar. Noise Corner < 100Hz
Back-to-Back Diodes	☑ May or may not be required. Check Data Sheet!	☒ Generally required	☑ Not required. Check Data Sheet
Integrated Digital?	☑ Yes. i.e. Chopper, package trim	☒ No	☒ No
Rail to Rail Input	☑ Yes	☒ No.	☒ Not common. Difficult
Rail to Rail Output	Very close to the rail. 10mV	Close to the rail. 200mV	Same as bipolar
Output vs. Load	☒ Falls off quickly with load. Ron of output transistor.	☑ Relatively flat until you reach current limit. Vsat not related to Ron as with CMOS.	Same as bipolar

Thank you