The State of Op-Amps

What designers have devised during the past year or so to improve in every way the ubiquitous operational amplifier

By Dan Becker

Operational amplifiers were originally built from discrete transistors, capacitors and resistors on printed-circuit boards. These "subassemblies" served as basic building blocks for exotic analog instruments and computers. Built from discrete components, early op amps were expensive, bulky and power hungry. They reigned supreme in their own special nook until the 1960s when advancements in semiconductor processing, in the form of integrated circuits, made possible entire circuits on a single silicon "chip." The introduction of integrated-circuit technology to semiconductor manufacturing suddenly made it practical to mass-produce miniature, low-power op amps. And because IC op amps were low in cost, even back then, applications began to grow at a tremendous pace.

One of the earliest of the successful op-amp designs was the historic 741 device, which quickly became the foundation for many new circuits and projects. So entrenched has the 741 become that it remains in wide use even today, its pinout arrangement a generally accepted industry standard for op-amp devices. But time marches on, and so does technological development. Improved and pin-compatible JFET op amps are now often used in place of the original all-bipolar 741 and similar op-amp versions.

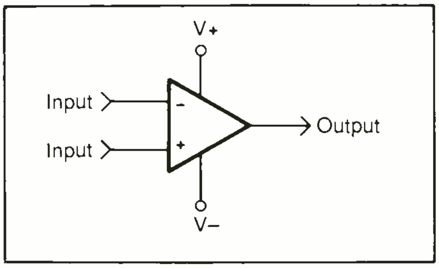


Fig. 1. The commonly accepted schematic symbol for the operational amplifier.

Setting the Stage

Although the schematic symbol for the operational amplifier, shown in Fig. 1, has not changed over the years, performance levels of the newest state-of-the-art devices have dramatically improved. Circuit designers continue to make steady progress toward achieving previously unheard of performance:

- Unity-gain bandwidths of 5 gigahertz
- Input bias currents of 40 femtoamperes
- Slew rates as high as 1,400 volts/microsecond
- Input offsets of 40 microvolts
- Input noise of 1.1 nanovolts/$\sqrt{Hz}$ at 1 kHz

All of these are realizable goals, though not currently all in the same device.

To achieve this kind of performance, op-amp manufacturers devised and combined several new technologies. Some combine special circuit designs with newly developed semiconductor processes, most using their own combinations of new techniques to achieve high-performance products. At the present time, it is impossible to find a single op amp that contains the best of all features. However, with the rapid pace of development in this industry, it may not be long before even this will be possible.

During the past year, many new high-performance IC op amps have become available. Each excels in one or more areas and exhibits outstanding overall specifications. Since some of these hot new op amps are even targeted for consumer products, there is a good chance that not too far in the future they will show up in the experimenter/hobbyist marketplace.

Each of the new generation of op amps generally falls into one of three price/performance categories: JFET-input devices, MOS-input devices and bipolar-input devices. Details of these three different types of devices are illustrated in Fig. 2.

JFET devices generally feature lower input bias and difference currents and lower offset voltages, and they are less affected by changes in temperature than are their MOS and bipolar counterparts. Specifications are often stated in terms of "guaranteed" values.

JFET noise performance in the 1-to-10-Hz range (1/f noise) may be as much as 10 times better than for comparable MOS devices. Prices for these devices range from about $8 to $75 or so in OEM (original equipment manufacturer) quantities of 100 or more pieces.

Latest-generation MOS-input op amps offer cost-effective solutions to many circuit design problems for which heretofore no solutions what-

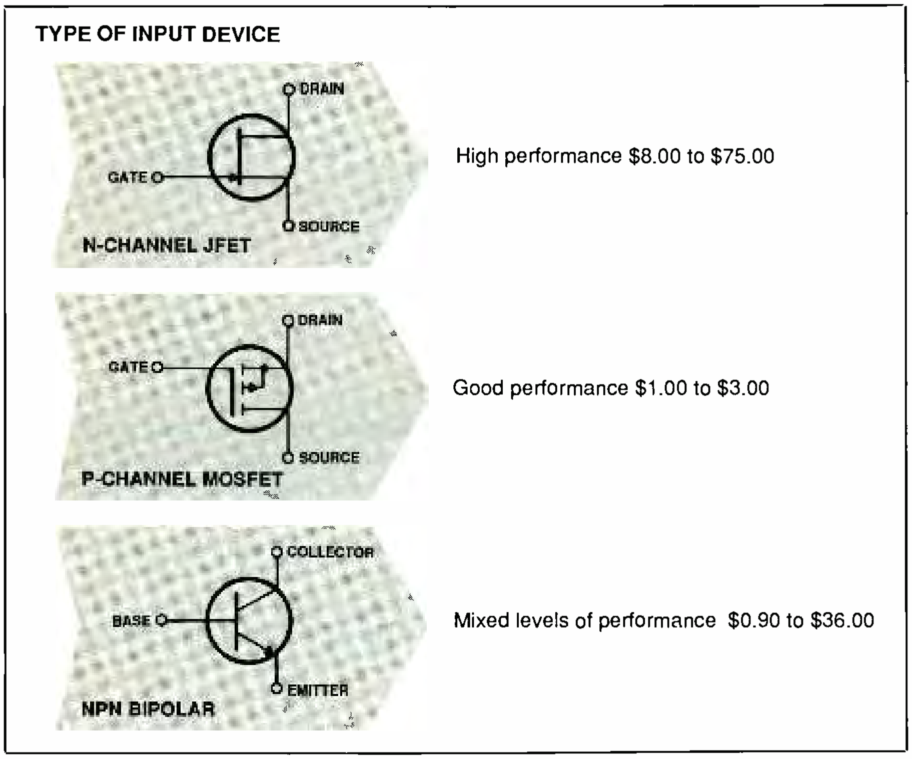


Fig. 2. How the three types of op-amp input devices relate to each other in price/performance.

ever existed. Although their specifications may closely parallel those of JFET devices, values for MOS devices are often given in terms of "typical" (not guaranteed) performance. Prices for these devices range from about $1 to $3 or more in OEM quantities.

Op amps with bipolar input transistors have features that vary over a wide range and offer unparalleled performance in many specific areas. Prices for these devices also vary widely, depending on combinations of features and levels of performance.

User Friendliness

Manufacturers are increasingly aware of the need to make products and devices "user friendly." For op amps, this means simplifying operation over a wide range of supply voltages and temperatures. The present industry trend is toward making op amps that can operate from single-ended power supplies, mainly the 5 volts popularly used in digital and many analog circuits, in addition to more conventional and traditional split supplies. Moreover, because operation from the new 3.3-volt standard is now an important consideration, some op amps can already meet this requirement.

As with input bias current, limiting quiescent power dissipation is of major interest in many applications. Reducing power requirements puts less of a demand on system designers and the power supply components used, making user friendliness a practical reality.

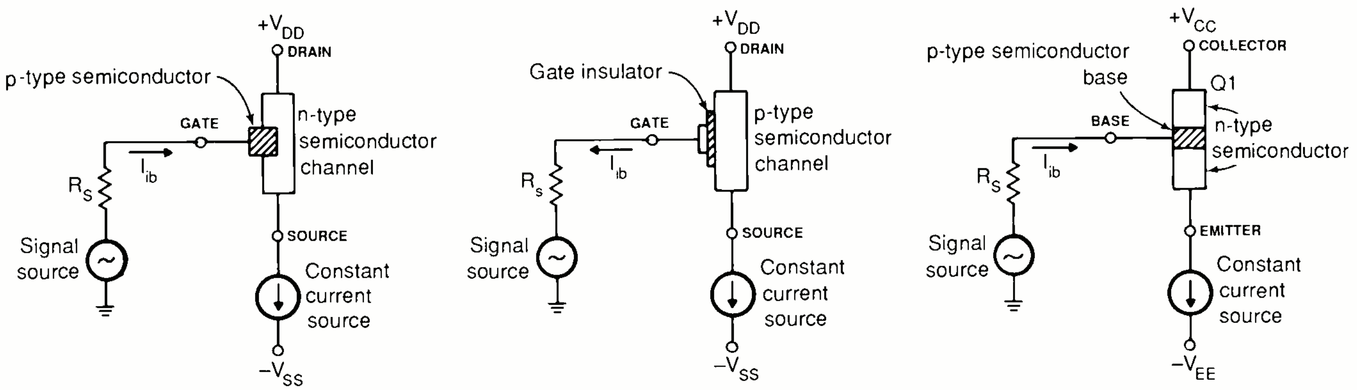
Let us now examine a few of the most important operational amplifier features:

- *Input Noise.* Much of the difference in cost between JFET and MOS op amps lies in the difficulty and length of time required to precisely measure and/or ensure a given IC's performance. For example, if a 1/f noise is an important consideration, op amps with JFET input transistors often come with more complete noise performance information. Generally, JFET data sheets specify both typical spot noise (noise at only one frequency) and typical broadband noise. JFET devices can give as much as 10 times better 1/f noise performance than MOS-input devices. Typical JFET spot noise, measured from 0.1 to 10 Hz, is 4 microvolts peak-to-peak. Typical broadband noise, measured from 10 Hz to 10 kHz, is generally 2.4 microvolts., Spot noise at 10 kHz may also be specified.

You should keep in mind that there are always exceptions to any rule. Linear Technology's LT1028 op amp is a case in point. Designed to amplify signals of a few millivolts or less from low source impedances, this bipolar op amp features input noise figures of 1.9 $nV/\sqrt{Hz}$ at 10 kHz, 1.1 $nV/\sqrt{Hz}$ at 1 kHz and 90 nV p-p over a range of from 0.1 to 10 Hz. These levels are well below those for FET devices. However, as good as they are, input current noise levels for the LT1028 cannot compete with those of certain MOS devices in which noise currents are almost nonexistent.

Noise figures are given as typical values because of the high cost of measuring noise in a production-line environment. When you consider that 1.6 minutes is required to accumulate 10 cycles of 0.1-Hz noise, you can well understand why many manufacturers give typical noise ratings. To give actual (or guaranteed) noise figures would be prohibitively expensive in all but an almost infinitesimally small number of cases. Nevertheless, because input noise is often the limiting factor in voltage measurement resolution, manufacturers continue to strive for product improvements, even if this means added expense.

- *Input Bias Current.* In a similar way, accurate measurement of input bias currents in the femtoampere range is also difficult to perform and



(A) JFET. Dc gate leakage current flows through signal source and across reverse-biased pn junction (gate junction) and into the n-channel. Gate leakage current is an undesirable effect.

(B) MOSFET. Dc gate leakage current flows through gate insulator and signal source and into p-channel. Gate leakage current is an undesirable effect.

(C) Bipolar. Dc base (bias) current flows through signal source and into base-emitter junction, forward biasing Q1. Base current is an essential part of bipolar transistor operation.

Fig. 3. Fundamental sources of input bias current (I_{ib}) for the JFET (A), MOSFET (B) and bipolar (C) transistor.

adds to production-line costs. Guaranteeing input bias currents and input difference currents in the femtoampere range is what separates higher-priced JFET devices from their lower-cost companions whose input bias and difference currents are given only in terms of "typical" performance. Therefore, this and other similar processing technologies offer vast improvements in performance, though at a price that is relative to performance predictability.

To minimize input bias current in both JFET and MOS devices, input stages use field-effect transistors, or FETs, that are often special versions of junction field-effect transistors, or JFETs. They include dielectrically isolated (DI) JFET, the junction-isolated FET, PMOS and silicon-gate CMOS devices. All these special transistors are used because of their extremely low input bias (leakage) current characteristics. Bias currents amounting to as few as 60 electrons per millisecond (1 femtoampere) are achieved. Figure 2 shows details of these transistor devices.

Typical applications requiring low input bias currents include integrators, current-to-voltage converters and log function generators. In addition, many transducers exhibit high internal resistance. These include transducers for measuring pH, photodetectors, accelerometers and numerous piezoelectric devices.

Consider a transducer with a high internal resistance connected to the input of an op amp. Input bias current flows through the transducer (signal source in Fig. 3), which causes a voltage drop across the transducer and is equal to the bias current times the transducer's resistance. This kind of input voltage reduces the accuracy and resolution of a measurement. The low input bias current op amp minimizes this type of error voltage.

● *Offset Voltage*. Examining data sheets on these new op amps makes it apparent that offset voltages are down significantly from where they were just a short time ago and that JFET devices often exhibit better performance in this area than other devices. In some cases, lasers are used to trim the minute semiconductor components of the JFET's input stage to "tweak" the offset voltage to within guaranteed values. Because this is an added manufacturing expense, it inevitably shows up as an increase in the cost of the device to OEM users and, ultimately, end purchasers of any product in which these devices are used.

● *Temperature Effects*. Input bias current, input difference current and input offset voltage all drift (change) with changes in temperature, which accounts for one of the major sources of error in most precision applications. Therefore, it is important to minimize these factors at all temperatures. As one example of temperature's influence on device performance, for every 10-degree celsius increase, input bias current will approximately double. Hence, manufacturers usually state a maximum bias current at 70 degrees celsius (125 degrees celsius for military versions) for op amps with JFET inputs. Alternatively, some op amps feature bootstrapped inputs and external pins that permit nulling the bias current and/or offset voltage.

● *Static-Discharge Protection*. Unfortunately, diodes must be connected across the inputs to protect the sensitive gates of the FETs used in op-amp input stages from damaging static discharges. These diodes

Performance Specifications for Some New High-Performance Integrated-Circuit Operational Amplifiers

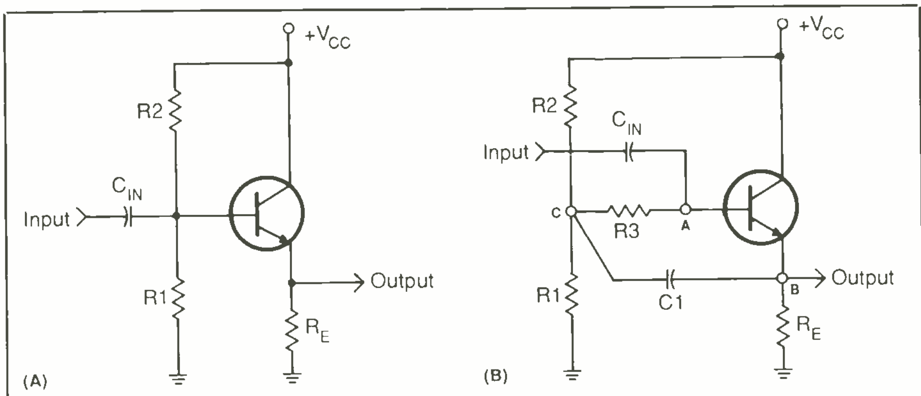
Manufacturer	Device	Single/Split Supply Voltage	Supply Current	Input Type	FP*/UG** Bandwidth	Input Bias	Input Offset	Slew Rate (Vμs)	100-pc. Price Ea.
Advanced Linear Devices 1030 W. Maude Ave. Suite 501 Sunnyvale, CA 94086	ALD1701	2 ~ 12/ ± 1- ± 6	250 μA	MOS	NA/700 kHz	1 pA	1 mV	0.7	$1.83
Anadigics Inc. 35 Technology Dr. Warren, NJ 07060	AOP3510	NA	NA	Bipolar	70 MHz/ 350 MHz	NA	NA	1,200	$32.75
Analog Devices Inc. Semiconductor Div. 804 Woburn St. Wilmington, MA 01887	AD549L	NA/ ± 15	200 μA	JFET	NA/700 kHz	60 fA	500 μV	2	$15.45
Burr-Brown Corp. P.O. Box 11400 Tucson, AZ 85734	OPA-128L	NA/ ± 15	NA	JFET	NA/500 kHz	75 fA	500 μV	1	$23.95
	OPA-128K	NA/ ± 15	NA	JFET	NA/500 kHz	150 fA	500 μV	1	$18.95
	OPA-128J	NA/ ± 15	NA	JFET	NA/500 kHz	300 fA	1 mV	1	$12.50
	OPA-600	NA/ ± 15	NA	FET	NA/5 GHz	20 pA	NA	NA	$75.00
GE RCA Solid State Route 202 Sommerville, NJ 08876	CA5422	2 ~ 10/ ± 1 ~ ± 10	400 μA	MOS	NA/160 kHz	160 fA	1.8 mV	0.25	$1.95
Harris Corp. Semiconductor Sector P.O. Box 883 Melbourne, FL 32901	HA-5151	2 ~ 10/ ± 1.5 ~ ± 15	250 μA max.	Bipolar	80 kHz/NA	70 nA	500 μV	4.5	$5.20
Linear Technology Corp. 1630 McCarthy Blvd. Milpitas, CA 95035	LT1028	NA/ ± 15	12 mA	Bipolar	NA/50 MHz	260 nA	40 μV	11	$4.95
Motorola Inc. Bipolar Analog Integrated Circuits Div. 7402 S. Price Rd. Tempe, AZ 85282	MC33171	NA/ ± 15	180 μA	Bipolar	NA/1.8 MHz	NA	1 mV	2.1	$0.90
National Semiconductor 2900 Semiconductor Dr. Santa Clara, CA 95051	LC66OC	3 ~ 16/ ± 1.5 ~ ± 8	2.9 mA	MOS	NA/1.5 MHz	40 fA	1 mV	1.7	$1.45
Plessey Semiconductors 9 Parker St. Irvine, CA 92718-2892	SL2541	NA/ ± 15	NA	Bipolar	40 MHz/ 2.5 GHz	NA	NA	1,400	$35.49
Precision Monolithics, Inc. 1500 Space Park Dr. P.O. Box 58020 Santa Clara, CA 95052	OP-80	2.5 ~ 8/ ± 5	NA	MOS	NA/300 kHz	100 fA	1 mV	0.2	$1.40
	OP-90	1.6/ ± 0.8	20 μA	Bipolar	NA/25 kHz	5 nA	NA	0.008	$2.75

*FP = Full-Power. **UG = Unity-Gain.

create an additional problem because their shunting action reduces the amplifier's input impedance. To counteract the undesirable effects of the diodes, while ensuring static protection to 1,000 volts or more, several ingenious bootstrapping techniques are employed. Figure 4 illustrates how bootstrapping counteracts the impedance-lowering effect of shunting components.

Mixed Technology

With power-supply potentials in the 2-to-15-volt range, bipolar transistors operate more efficiently than do FET devices when driving low-impedance loads. Therefore, with or without FET input devices, op amps inevitably use an all-bipolar output stage. One example is RCA's line of BiMOS (for bipolar metal-oxide semiconductor) devices (Fig. 5). A high-performance dual op amp like RCA's CA5422 combines MOS devices at the input stage with bipolar transistors in the output stage. These more conventional output transistors produce minimal quiescent power dissipation while providing the capacity to drive a low-impedance load.



(A) A one-transistor voltage follower without bootstrapping has an input impedance that can be as high as 1 megohm. However, because the power supply (V_{cc}) acts like a short circuit for ac signals, bias resistors *R1* and *R2* are effectively in parallel and shunt the input signal to ground. This lowers the circuit's input impedance to that of the parallel equivalent of *R1* and *R2*. **(B)** Same circuit with dc bias network *R1/R2/R3* bootstrapped. Input impedance is about 1 megohm. Output signal voltage at point B is equal in amplitude and in-phase with input signal voltage at point A. Output signal voltage is connected to point C via *C1* to place equal and in-phase signal voltages at both points A and C and prevent input signal current from flowing through *R3*. Because it is isolated from dc bias network, point A is a high-impedance input. A similar bootstrapping technique is used in op amps to overcome low-impedance shunting effects of static-protection diodes.

Fig. 4. The principles of bootstrapping: a circuit without bootstrapping (A) and the same circuit with bootstrapping (B).

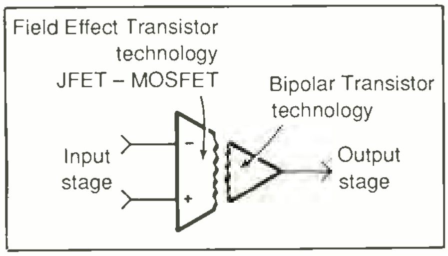


Fig. 5. A depiction of the modern combined-technology op amp.

There are several important points to consider when deciding on a specific op amp for a given application. Some of these include all of the above (input offset voltage, input bias current, input difference current and temperature stability) as well as bandwidth, quiescent power dissipation, slew rate, output drive current and, frequently just as important a factor as electrical performance, cost.

The new generation of op amps makes selecting an operational amplifier for a particular application an even easier task than it has been in the past. These new op amps open a whole new world of possibilities to the professional and hobbyist alike. As a result, test instruments with higher resolution, greater accuracy and the ability to measure much smaller currents will eventually reach the consumer. In the Table shown elsewhere in this article, we have listed several high-performance op amps from several different manufacturers, along with a number of their most important specifications. If you would like to get a headstart on these devices before they actually become generally available, you can write to the manufacturers to request advance data and applications sheets.