Objective This is an introductory experiment which, within the context of basic semiconductor diode circuits, reacquaints students with laboratory rules, procedures, equipment, and course requirements as well as properties and representative applications of semiconductor diodes.

Parts:
- junction diodes ............... 5 of 1N4004
- 1 Zener diode (5.1 volts) ...... 1N5231
- sampling resistor pair ........... as provided
- resistors ..................... 4.7 Ω, 68 Ω, 5 of 100 Ω, 2 of 125 Ω, 1 kΩ, 5 of 3.3 kΩ, 6.8 kΩ
- capacitors .................... 0.1 µf, 10 µf

Idealized Diode
'Real' circuit elements such as resistors, capacitors, and inductors are approximations to the idealized circuit elements of the same name. An adequate description of the circuit properties of a real resistor for example, particularly at higher frequencies, involves idealized inductors and capacitors as well as an idealized resistor. The idealized circuit elements each represent a conceptually distinct type of circuit behavior, a conceptual separation which is at best only approximated in practice over a limited range of operation.

A semiconductor PN junction diode (in particular) represents a real world approximation to such a conceptually distinct kind of circuit behavior; its terminal properties are characterized primarily by non-bilateral behavior. The idealized diode is a two terminal device whose terminal properties depend on the direction of current flow through the diode and the polarity of the terminal voltage difference across the diode. These terminal properties are defined in the drawings to the right, above. The word 'defined' should be noted carefully, because it is important to understand that the
idealized diode is not a device actually existing in nature, although its characteristics are approximated by several real devices. It is a definition of a functional relationship, represented pictorially by the 'arrow' icon as shown. For the present we consider only the idealized device, but later we consider real-world approximations to the idealized device.

The diode icon may be used to recall polarity conventions for the terminal voltage and current corresponding to the definition above. A non-zero current flows only in the direction suggested by the icon 'arrow' and, unlike a resistor for example, no power is expended in the device by this flow; the diode voltage is zero whenever any current flows. The upper of the algebraic expressions corresponds to the vertical segment of the diode characteristic. In contrast to this 'easy' direction of current flow in 'forward bias' the device is open-circuit for any 'reverse bias' voltage. The diode behaves in a sense as a switch, open to prevent current flow in one direction and closed to allow it in the other direction. Unlike a mechanical switch however the diode is 'opened' or 'closed' simply by virtue of the current and voltage polarity involved.

Because the switch-like circuit behavior of the idealized diode does not depend on some sort of switching mechanism controlled from outside a circuit it can be used to change automatically the effective electrical topology of a circuit. Consider, for example, the circuit drawn to the right, consisting of an idealized diode in series with a DC voltage source. The voltage drop across the diode (in the direction of easy current flow) is V-V_o. So long as this voltage difference is non-positive the diode is reverse-biased, and the diode property is that no current flows for this condition. If current does flow it must do so in the 'forward' direction, and the voltage drop across the diode, i.e., the difference V-V_o, then is zero. The overall volt-ampere characteristic is drawn besides the circuit diagram in Fig. 4.2.

'Experiment 4.1A: Curve Tracer Display'
The theoretical volt-ampere characteristic of a real semiconductor junction diode has an exponential form which is well approximated in many circumstances by the two-segment characteristic of the preceding model. Display the volt-ampere characteristic of a 1N4004 junction diode (or equivalent) on the laboratory curve tracer over a nominal forward current range of 0 to 10 milliamperes, and for reverse bias voltages up to 15 volts or so (expand the current scale appropriately). Compare the general range of forward and reverse-biased currents and voltages. Determine a value of V_o for a two-segment idealized diode approximation, and state the reasons for which you selected this 'breakpoint'. Keep in mind that the two segments model the diode characteristic over the full range of the measured characteristics. The approximate curve should be related to the actual diode characteristic in a carefully drawn and labeled sketch. The laboratory instructor will set up for future reference a display of the 1N4004 diode characteristics operating in the reverse breakdown region, and also the 1N5231 Zener diode characteristics.

Experiment 4.1B: Clipping'
Assemble the circuit as shown to the right with the 0-20 VDC diode 'offset' voltage source set to 0 initially, and use the X-Y input setting to display the voltage transfer characteristic (V_out vs V_in) dynamically on the oscilloscope. Drive the circuit (V_in) with the triangular waveform (0 volts DC offset) from the function generator using the maximum undistorted output amplitude and a nominal 1 millisecond period. Quantitatively relate the observed transfer characteristic to the theoretically expected characteristic.

Observe the displayed voltage transfer characteristic for offset voltages of 2 and 5 volts. Describe and explain your observations. If they are not in accord with what you expected explain why not. What is the
voltage at which the observed characteristic 'breaks' when the offset voltage is set to 2 volts? Why is this breakpoint voltage different from that estimated using an idealized diode model?

Observe both $V_{in}$ and $V_{out}$ vs. time concurrently on the oscilloscope. Set the DC offset voltage to 3 volts, and observe the effect on $V_{out}$. Describe and explain your observations, relating them to theoretical expectations.

**Zener Diode Shunt Regulator**

Ordinarily the reverse-bias blocking action of a PN junction allows only a small 'leakage' current to flow. However if a sufficiently large reverse bias is applied phenomena other than junction effects occur, allowing much larger reverse-bias currents. This is the 'breakdown' part of the diode characteristic; 'breakdown' here refers to the overshadowing of the semiconductor junction behavior by other phenomena rather than to some physically destructive effect. While all diodes display this breakdown phenomena some diodes are manufactured specifically for operation in the breakdown condition with guaranteed specifications. The breakdown parameters of these Zener (or voltage reference) diodes receive special attention during their manufacture and testing.

An illustrative breakdown characteristic is drawn to the left. The nominal Zener reference voltage of the diode is the reverse bias voltage at which a manufacturer-specified 'test' current $I_{ZT}$ flows. In general the Zener voltage is a function of temperature; a representative temperature specification is 0.1% change per °C change. The coefficient is negative for a diode with a reference voltage below about 5 volts, otherwise positive.

The inverse of the slope of the diode characteristic at the test point is called the 'dynamic resistance' of the diode and is a parameter noted in the manufacturers' specifications; the slope of the characteristic does not vary greatly for currents in the range (roughly) between $0.1I_{ZT}$ and $I_{ZT}$, a usual range of operation of a Zener diode. (Note that the scale for the figure is distorted for illustrative purposes.)

A piecewise linear representation of the Zener characteristic applicable over the range of normal operation of the Zener diode (i.e., in breakdown and reverse bias) may be used for rough calculations; one such representation is shown in the figure to the right, together with an idealized diode equivalent circuit. (Do not confuse the idealized diode used in the model with the Zener diode whose characteristic is being modeled; the actual device characteristic is being approximated over a limited range of operation by a combination of idealized device characteristics.

An illustrative circuit application of a Zener diode, illustrated by the circuit diagram below, is a 'shunt voltage regulator': $V_S$ and $R_S$ represent the Thevenin equivalent circuit as seen looking into the terminals of a power supply, and $R_B$ and the Zener diode serve as a control devices to regulate the voltage across the load $R_L$. Absent the regulating elements an increase in load current (by reducing $R_L$) produces a larger 'internal' power supply voltage drop across $R_S$ and consequently a lower power supply terminal voltage. This variability is measured by the 'regulation' of the power supply, defined formally as the change in terminal voltage.

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between 'no load' and 'full load' conditions, divided by the 'no load' voltage. It is essentially a measure of the effect of the internal resistance of the supply on the terminal voltage as the load current changes from one to the other extreme of its specified range.

Adding the Zener diode modifies the load as seen by the supply, i.e., looking out of the supply terminals toward the load. Insofar as the power supply is concerned its load current consists of the current drawn through $R_L$ plus the added current drawn by the Zener diode. The total load current, from the point of view of the power supply, is larger than what it would be absent the Zener diode and $R_B$.

To the extent that the Zener voltage is constant the circuit maintains a constant supply current, dividing that current between the Zener diode branch and the actual load. The qualification reflects the fact that the Zener resistance $r_Z$ is not exactly zero, and so the Zener voltage varies somewhat as the diode current varies. The essential idea is to shunt 'excess' current through the Zener when $R_L$ is a maximum, and then decrease the amount of this diversion as load current demand increases. The power supply itself 'sees' a more or less fixed current, and so its terminal voltage changes little. The fixed supply current divides to provide the load current, with the remaining current going to the diode. The Zener diode provides an approximation to a constant voltage source, and $R_B$ provides an automatically adjustable voltage drop between the supply voltage and the Zener regulated load voltage.

The regulating action is indicated in the curves obtained by an analysis of the circuit using the piecewise-linear Zener diode approximation described before. The unity slope reference line (dashed) is the voltage transfer characteristic of the power supply alone, i.e., when the regulating elements are removed so that $V_L = V_S$.

The other curve (solid) describes the circuit with the regulating elements inserted. As soon as the load voltage (voltage across the diode) reaches the Zener breakdown voltage the overall load resistance seen by the supply becomes nearly constant, $\approx R_B + r_Z || R_L$, $\approx R_B + r_Z$ assuming (as likely would be designed in) $r_Z \ll R_L$. 

![Fig. 4.6 Regulated power supply](image)

![Fig. 4.7 Regulator characteristics](image)
An important implicit qualification that should be recognized is that regulation depends on operation of the Zener diode in its breakdown region. This is not something that happens automatically; it must be designed in properly. It means enough current must be drawn by the Zener diode to maintain breakdown operation, even in the 'worst case' situation when the maximum load current has been siphoned off from the supply current, i.e., at the minimum diode current. Hence at full-load current one should design the circuit for a Zener current of roughly 0.1 $I_{ZT}$. On the other hand when the load draws the minimum current the increased current through the Zener should not exceed the rated $I_{ZT}$. Between these operating requirements, and of course knowing the (nominal) Zener diode voltage, an appropriate value of $R_B$ can be calculated.

The calculation is particularly interesting because it is different from solving for specific values as is done in introductory circuits courses. Two extreme ('worst-case') conditions are involved in the form of inequalities, not equalities. The result of the calculation is not the value of the resistance to use but rather inequalities which specify use of a resistance which is greater than some value but less than another. What would it mean if, as is entirely possible, the upper bound was less than the lower bound?

**Experiment 4.2: Zener Regulator**

The commercial laboratory power supply is designed to be very well regulated; in fact it includes special regulation circuitry. To simulate a relatively poorly regulated power supply for purposes of this experiment place a resistance of 47 $\Omega$ in series with the power supply, and consider this resistance to be part of the 'internal' resistance of a poorly regulated supply, i.e., $R_S$. Thus the 'supply terminal voltage' for this experiment is measured at the terminals outside the dashed box (see circuit diagram above). Set the no-load (open-circuit/Thevenin) supply voltage to 15 volts by adjusting the laboratory supply. The nominal 'test point' breakdown voltage of a 1N5231 Zener diode, read from the manufacturer's specifications, is 5.1 volts @ 20 milliamperes; the Zener resistance $r_Z$ is 17 $\Omega$. Design a shunt regulator for load ($R_L$) currents varying from a maximum of 15 ma down to a minimum of 2 milliampere (nominal values). From the previous discussion note that this requires satisfying two conditions one of which sets an upper limit on the value of $R_B$ allowed, with the other condition setting a lower limit. Select an appropriate resistance value; use a composition resistor and not a potentiometer. Take data for your regulated supply sufficient to plot the load voltage as a function of load current, and the power supply terminal voltage (remember: outside the dashed box) vs. the load current. Compare graphically the voltage transfer characteristic (load curve) computed for your design with the measured characteristic of the actual circuit. Include quantitative comments in your writeup about the efficiency of the regulation, e.g., compare the supply power to the load power to appreciate the energy cost of maintaining a regulated output voltage with your regulator.

Suppose the voltage $V_S$ increases for some unspecified reason. How is the regulation affected?

**Piecewise Linear Function Synthesis**

Absent the diode branches (in the circuit to the right) $V_{out}$ and $V_{in}$ are linearly related; in fact $V_{out} = V_{in}$. However because of the diodes and their associated offset voltage sources successive branches become 'active', i.e., diodes are forward-biased, at successively higher values of $V_{out}$ (and so $V_{in}$). Each time a shunt branch becomes active the electrical topology of the circuit changes, consequently changing the relationship between $V_{out}$ and $V_{in}$.

For voltages such that $N-1 < V_{out} < N$, where $N$ is an integer, the several diode offset voltages are such that the first $N-1$ branches (from the left) are active. These active shunt branches can be replaced by an equivalent circuit as follows. Convert each active shunt branch to its Norton equivalent (resistor with resistance $R/2$ in parallel with a current source $2V/R$, where $V$ is the integer value of the diode voltage
source offset). The parallel combination of N-1 such resistors has an equivalent resistance of \((R/2)/(N-1)\). Since the current sources all are in parallel the cumulative current is the sum \((2/R)(1+2+...N-1) = N(N-1)/R\). Convert the Norton equivalent circuit to its Thevenin equivalent to determine that the Thevenin equivalent of all the active shunt branches is a resistor whose resistance is \((R/2)/(N-1)\) in series with a voltage source \(N/2\). From this equivalent circuit it can be determined that \((2N-1)V_{\text{out}} = V_{\text{in}} + N(N-1)\) for \(N-1 < V_{\text{out}} < N\).

As substitution in the equation verifies the circuit values have been chosen so that when \(V_{\text{out}} = N\), \(V_{\text{in}} = N^2\). Note that this relationship applies only at the voltage breakpoints at which the diode branches successively cut in; between one breakpoint and the next the output voltage varies linearly. Thus the transfer characteristic has an output voltage exactly equal (theoretically) to the square root of the input voltage at specific voltages, and at intermediate voltages is a piecewise-linear approximation to a square root characteristic. The PWL input/output characteristic is drawn to the left. A continuous square-root characteristic can be sketched to indicate semi-quantitatively the degree of approximation obtained.

Verify the correctness of the general expression for, say, \(9 \leq V_{\text{in}} \leq 16\) by direct analysis of the circuit for this condition.

'Experiment 4.3: Square Root Transfer' The idealized diode PWL circuit is approximated by the more practical circuit shown below. In this circuit the 'r' resistive voltage divider is used to develop the set of nominal diode offset voltages as shown. The value of r is chosen to be small enough compared to the branch resistances so that for each shunt branch the Thevenin equivalent circuit looking into the divider is very nearly a voltage source of the specified value, with a resistance which is small compared to \(R/2\).

Assemble the experimental circuit using the indicated resistor values. However before measuring (and plotting) the experimental voltage transfer relationship a calibration adjustment should be made. The voltage transfer characteristics of both the idealized and practical circuits both have zero output voltage for zero input voltage, i.e., there is an excellent match between theory and experiment at the origin. A second point of close agreement between theory and practice can be forced by adjusting the nominal 15 volt voltage-divider supply so that, say, \(V_{\text{out}} = 4\) volts when \(V_{\text{in}} = 16\) volts, i.e., make theory and experiment match toward the upper end of the experimental scale. (Note: although the circuit design shown allows for input voltages greater than 25 volts most of the laboratory supplies provide 20 volts maximum. In this case the last diode branch on the right may be omitted since that diode will not be able to become forward-biased.) This calibration more or less forces improved agreement between the experimental and theoretical curves at intermediate points (Why?).
Take data sufficient to plot the experimental voltage transfer relationship adequately. Superimpose these data on a plot of the theoretical square root characteristic $V_{out} = \sqrt{V_{in}}$ for comparison. You will find it useful to plot $V_{out}$ vs. $\sqrt{V_{in}}$ rather than vs. $V_{in}$; theoretically the square-root plot then should be a line with unit slope so that a laboratory plot of data as it is taken readily indicates the reliability of the data. Estimate (from your data/graph) the maximum difference between the piecewise linear approximation and the experimental characteristic. Is this difference an 'error'? If so why? If not, why not?

**Diode Rectifiers**

For many if not most purposes a DC voltage supply is preferred as the energy source for a circuit. A voltage source supplies no current in a standby condition (except small internal maintenance currents), and so relatively little standby power is expended. A DC voltage has the advantage of not introducing any special timing synchronization considerations other than turn-on and turn-off transients. Hence a 'local' DC voltage supply is a ubiquitous part of most electronic equipment. However except for a relatively limited use of such DC sources as batteries a voltage supply actually is an electrical power converter; it converts more conveniently generated sinusoidal AC power, 60 hertz is common, to DC power. This conversion typically is a two step process. First the AC input is 'rectified', i.e., converted to a varying but unipolar output, and then this unipolar output is 'filtered', i.e., the size of the variation is reduced.

The 'half-wave' rectifier circuit illustrated to the right uses unilateral operation of a diode to rectify a sinusoidal input; the diode is forward-biased only during the positive half-cycle of the sinusoid, and it is only during that cycle that current flows through the load resistor. This relationship is indicated by the shaded waveforms.

The negative rather than the positive half-cycle can be used to pass current simply by reversing the diode orientation. Of course the direction of current flow through the load resistor changes also if this is done.

Two half-wave rectifier circuits, one active during the positive half-cycle and the other during the negative half-cycle, can be coordinated so that both half-cycles supply a unidirectional current through the load resistor. One way to accomplish this, the circuit is called a 'full-wave bridge' rectifier, is illustrated to the left.

Two rectifier circuits are combined as illustrated to provide separate current paths through the load resistor. When the two diodes associated with one circuit are conducting the two for the other circuit are reverse-biased and do not conduct. The two rectifiers operate essentially independently on alternate half-cycles of the input. However as an examination will reveal the current associated with the rectification flows in the same direction through the load resistor whichever diode pair is active. Although certainly not a DC voltage the unipolar full-wave output voltage is 'closer' to DC, at least in the sense that the average value is not zero.

Transformers also are used to provide full-wave rectification circuits. The use of transformers also provides voltage stepup or step-down capability, as well as DC electrical isolation between primary and secondary, albeit at the cost of the transformer bulk and weight. Two transformers, often conveniently assembled as a combined unit with a continuous center-tapped secondary winding on a single magnetic...
Core, are used to provide two equal secondary voltages 180° out of phase with each other. Hence, while both diodes conduct on a positive (forward-bias) half-cycle of the respective secondary voltages these correspond to opposite half-cycles of the primary voltages. As the diagram below indicates, the two rectifiers extract power from the primary during opposite half-cycles but both rectifiers feed current through the load resistor in the same direction to produce a full-wave rectified output waveform.

![Diagram](image)

**Fig. 4.13 Transformer-coupled full-wave rectifier**

**Experiment 4.4: Bridge Rectifier** Assemble a bridge full-wave rectifier using 1N4004 diodes and a 1 kΩ load resistor. Be sure the diodes are connected properly. Use a nominal 2 KHz sinusoidal signal from the waveform generator as the input source; the use of the higher frequency rather than 60 Hz makes for more convenient oscilloscope displays without sacrificing the basic principles to be examined. The 'real' diodes you use will have roughly a 0.7 volt forward-bias when they are conducting; be sure your input signal amplitude is large enough to be rectified! Display the input and output waveforms concurrently. Sketch your observations approximately to scale and describe their relationship to theoretical expectations. What is the effect of the finite diode voltage drop?

Carefully disconnect a diode to open-circuit one of the two rectifier paths; observe and explain the effect on the output waveform. Replace the diode and then open the other rectifier path; observe and explain the effect on the output waveform. Correlate both the latter observations with theoretical expectations.

**Capacitor-Filtered Rectifier**

Full-wave rectification still does not produce a completely satisfactory DC output voltage; the waveform must be filtered to remove some of the amplitude variation. The description 'filtering' is derived from an interpretation based on expanding the periodic rectified output waveform as a Fourier series, and then discriminating with a frequency sensitive voltage divider (as illustrated to the right) against all but the average (DC) term of the expansion. However a more physically oriented appreciation of the process is provided by interpreting it in the time domain rather than the frequency domain.

The output waveform amplitude could be 'smoothed' by providing additional energy during the valleys of the output to increase the amplitude. This could be done by introducing (and rectifying) additional AC sources properly phased in time; indeed three (and more) phase rectifiers for heavy duty industrial strength supplies are common. For ordinary purposes however energy may be taken from a single power source during the peaks of the rectified wave, stored temporarily, and then released to
the load in such a way as to smooth the overall energy transfer. A relatively simple way of doing this is to place a sufficiently large capacitor across the load resistor, as illustrated below for a diode bridge rectifier.

The capacitor (see illustration to the right) is charged by the AC voltage very quickly; in general the primary power source is able to supply a high charging current to the capacitor as well as the current drawn through the resistor. However this current must flow through forward-biased diodes, and as the capacitor charges to higher voltage eventually those diodes become reverse-biased. At that point the source is effectively disconnected from and no longer supplies energy to the load. However the capacitor then begins to discharge through the load, i.e., the charge stored in the capacitor becomes the source supplying resistor current. Because of the discharge the voltage across the capacitor decreases exponentially, a slower rate of decrease in general than the sinusoidal change. On the next half-cycle as the source voltage increases it will become larger than the decreasing capacitor voltage, the diodes again become forward-biased, and the capacitor is recharged to repeat the process.

The rate of decrease of the capacitor voltage is measured by the RC time constant, and to minimize the amount of voltage decay the time constant should be large compared to the source period. Note that this implies a small conduction angle, i.e., the diodes conduct only during a small part of the half cycle (typically a few degrees). The source provides power primarily to charge the capacitor; it is the capacitor that distributes power to the load more uniformly. A good estimate of the waveform parameters is made as follows: the half-period of a sinusoid of radian frequency $\omega$ is $\pi/\omega$. If the exponential decay is small, as it normally would be designed to be, then the exponential can be approximated closely by the linear terms of its power series expansion

$$e(t) \approx E_p (1 - \frac{t}{RC})$$

where $E_p$ is the peak sinusoidal voltage; $t=0$ is taken at the peak of the sinusoid, and the conduction angle is assumed small enough compared to the half-period to be neglected. At $t=\pi/\omega$ the output voltage has decayed to its minimum value. Hence the 'peak-to-peak' ripple, the difference between the maximum and minimum voltages is (approximately) $\pi/(\omega RC)$. The average value of the output amplitude is approximately the peak value less half the p-p ripple.

'Experiment 4.5: Filtered Power Supply' Add a capacitor filter to the bridge rectifier assembled earlier and observe the output waveforms. Superimpose the input waveform on the output display (dual trace) to obtain a composite picture of the filtering. Use both a 10 µf capacitor (connected with the proper polarity) and a 0.1 µf capacitor respectively; note (use the approximate analysis to estimate) quantitatively the
difference in the output waveform. Disable one of the rectifier paths to provide half-wave rectification, and observe the effect on the filtering. Describe your observations in an organized manner, including a comparison of the observed half-wave peak-to-peak ripple with an estimated value based on an analysis similar to the approximate computation described.

**Diodes Connected in Parallel**

On occasion several diodes may be connected in parallel so as to obtain a combined current handling capability greater than that of the individual diodes. In general it is preferable to use a single diode with appropriate higher ratings, assuming one is available, before resorting to paralleled operation. Serious complications may occur when paralleling devices; semiconductor diodes provide a convenient context in which to become better informed on this matter.

The root cause of problems is that the diodes, unless specially selected, will not have matched characteristics; matching includes not only a static commonalty but also tracking of changes with, say, temperature. With mismatched diodes connected in parallel a phenomena called 'current hogging' can occur, as illustrated in Fig. 4.17. Suppose for simplicity that just two diodes are connected in parallel, with individual volt-ampere relations as shown by the two curves to the right; ignore the dashed characteristic for the moment. The horizontal (voltage) displacement between the curves is exaggerated for clarity, and in practice typically would be only a few millivolts or less. The offset of the two curves could be a consequence of manufacturing tolerances or, for high currents, possibly a small difference in the resistance of a connection wire. Particularly for high currents, just the sort of circumstance where paralleling might be used, a small lead resistance easily can cause a few millivolts drop (e.g., 1 ampere across 1 milliohm for a 1 millivolt drop). Given the exponential dependence of semiconductor diode current on junction voltage a few millivolts difference in junction voltage results in a large current change (roughly, a 50 millivolts difference corresponds to an order of magnitude current change).

In the figure the diode currents are given by intercepts with a vertical line corresponding to the common voltage across the paralleled diodes; these are the I1 and I2 intercepts in the figure. As the figure suggests diodes can carry greatly disproportionate currents if their characteristics are not carefully matched. This current 'hogging' by a diode reflects on the current and power handling requirements necessary for safe operation; a design assuming near-equal current sharing could be seriously compromised.

The situation is aggravated further because of the temperature dependence of the diode characteristics. The junction voltage needed for a given current decreases (roughly 1 to 2 millivolts per °C at room temperature) as the diode temperature rises. If there is current hogging the diode carrying the higher current will dissipate more heat. Therefore it will run hotter, consequently draw more current because of the temperature effect, and thus increase further the disproportion in the current division. The dashed leftmost curve in the figure to the right represents the effect of heating on the diode characteristic; for a given voltage the diode current is higher and the characteristic moves to the left. This is a regenerative feedback condition and it is possible for a thermal runaway to occur, i.e., a diode pulls more current, gets warmer, pulls more current, etc. The ultimate result very likely is failure (open-circuiting) of the diode. This causes the current which was carried by the failed diode to be redistributed to the remaining diodes, with the not unlikely result that all of several paralleled diodes fail one by one in succession because of a progressive overloading.

Selecting diodes for matched characteristics is one preventative measure that can be taken, at a higher cost because of the special selection. That is one reason why the use of a single properly rated diode, in effect making matching inherent in the manufacturing process, has an intrinsic virtue when feasible.
On the other hand, and also at a cost, circuit changes can be used to guard against hogging. The figure to the left is a graphical load-line analysis of a circuit consisting of a diode in series with a resistor. The mismatched diode characteristics indicate the moderating effect of the resistor (a vertical dotted line indicating the current division for directly paralleled diodes is added for contrast). Of course the current flowing through the resistor dissipates energy, and naturally the more the moderating effect, meaning the higher the resistance, the more the dissipation. That is a 'cost' to be factored into a consideration of alternatives.

'Experiment #4.6: Paralleled Diodes'
The objective of this particular experiment is to demonstrate (safely) the content of the preceding remarks, and concurrently to suggest some of the difficulties which may arise in making sensitive measurements. While the current levels involved are not particularly dangerous to life and limb, they are lethal for the circuit components if misapplied. The power levels are sufficient to heat components to a point where they are literally destroyed; a relatively minor but annoying burn may reward excessive carelessness if this happens. Understanding and alertness are your best protection.

The circuit to the left uses a 68 Ω current-limiting resistor to hold the DC supply current to less than 300 milliampere; larger currents are well within the capabilities of the laboratory power supplies as well as within the diode ratings.

Measuring the diode currents without having the process of measurement affecting the current division is more difficult than might appear, since a few millivolts voltage difference can change diode current significantly. Inserting a meter in a diode 'leg' to measure current can affect the current division significantly; a 50 millivolt change in forward-bias junction voltage produces roughly an order of magnitude current change.

An adequate measurement for the present purpose is made using two closely matched resistances formed from a twelve inch (nominal) length of wire with a resistance of 0.44 Ω per foot; the two resistors have one common terminal at the center of the wire. This resistor is provided by the laboratory instructor. By measuring the voltage drop across each resistance the relative currents in each branch can be calculated without knowing the precise resistance. Note that even a 0.22 Ω resistor introduces a 22 millivolt drop for a 100 milliampere current.

The intrinsic asymmetry of the two diode branches because of the diode tolerances is exaggerated for this experiment by introducing a 4.7 Ω resistor in just one (either) branch. Thus 10 ma current through 4.7 Ω causes a 47 millivolt drop; reducing the junction voltage by this amount results (roughly) in an order of magnitude current reduction. Thus the current in the other branch would be roughly 100 milliamperes. The 4.7 Ω resistor simulates the effect of lead resistance in a high-current situation.

Assemble the paralleled diode circuit and compare the relative diode currents as the supply current is varied. Read total current from the supply to be able to calculate absolute current. Make sure the currents 'settle' before reading voltages, i.e., wait out any thermal changes that may occur. Check the suitability of the 68 Ω resistor you use before you power up the circuit. Plot the relative currents as a function of the supply current, and interpret the graph appropriately.
Modify the circuit as shown to the right, adding the series resistors in each branch to better balance the current division. Compare the measured current division in this circuit with that for the preceding one. Describe how the addition of the 125 Ω resistors helps balance the currents equally.

Did you check the power ratings of the 125 Ω resistors before you turned on the power?