cell is in the cryostat. Note that the stem (O) is subject to the same stability requirements previously mentioned for the pushtube (L). The force transducer housing (V) extends over the helium fill tube at the top of the cryostat. Therefore the stem (O) was made long enough to allow part of a split transfer tube to remain in the helium fill tube whenever the stress apparatus was in place, so that filling and refilling with liquid helium could be accomplished without disturbing the stress cell.

The bottom plate of the force transducer housing (V) is welded to the cylindrical housing wall. In order to be stable against a 10^9 dyne deflection force, the plate is constructed from 0.952 cm thick material. The connector housing has three 6-pin Amphenol vacuum-feedthrough connectors (W) (only one is shown in Fig. 1), attached to flanges welded to the housing. The bottom plate of the bellows section has a channel (X) through which nitrogen gas from a cylinder is admitted under pressure. The connection to the tubing delivering the nitrogen gas is accomplished through a right-angle bend and a Swagelock quick-connect (JJ).[10]

The outer bellows (Y) is welded to the top and bottom plates. The inner bellows (Z) is welded to the top plate and is soft soldered to a sleeve (AA) that is welded to the bottom plate and serves to equalize the heights of the two bellows. Both the inner (Z) and outer (Y) bellows were chosen with elastic limits of 2.5 cm, three times the distance the pullrod was calculated to stretch under a 10^9 dyne load. The guide rails (BB) are necessary to insure that the top plate remains parallel to the bottom plate as the force is applied. Holes are drilled in the top plate so that the guide rails (BB) can slide smoothly through it. The guide rails (BB) are threaded at the top and nuts (CC) are screwed on to retain the top plate in case of sample breakage. The top plate must be retained in order to prevent the bellows from being extended beyond their elastic limits. When samples have broken, only the sample cups were damaged.

The pullrod (G′) goes through the top plate and screws into a brass ball (DD) which seats in a spherical hole in the top plate. The ball (DD) is covered by a hat (EE) which provides a vacuum seal by seating against an O-ring. When necessary, a ring (FF) for hoisting the 18 kg stress cell is screwed into the hat (EE).

The force transducer (GG) is equipped with 1″–14 threads for connection to the applied force. This connection is made through adapters (HH) which contain 0.635 cm holes that provide passage for the pullrods (G, G′) which in turn screw into brass balls (II) that are confined by the adapters (HH). These brass balls prevent any transverse force from developing.

The force transducer (GG), a Schaevitz model FTA-2U-2K,[11] has a cylindrical shape with a 7 cm o.d. and a 10 cm length. It measures force in the range 0–10^9 dynes by sensing the displacement of an elastic mechanical element coupled to a linear variable differential transformer (LVDT). The transducer produces an ac electrical output which is converted to a dc output by a Schaevitz model GPM-101 model. The force transducer and the module are calibrated as a unit by the manufacturer. The force transducer's specifications are: linearity better than 0.2% of full range, resolution and repeatability, both better than 0.1% of full range. The LVDT was hermetically sealed to prevent water vapor damage.

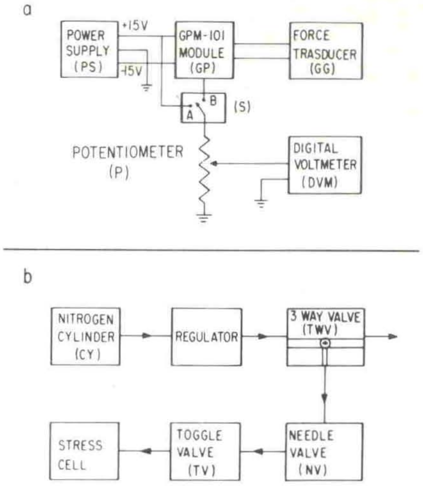

FIG. 3(a). A block diagram of the electronics used for a direct stress readout. (b) A block diagram of the pressure control apparatus.

As previously stated, the GPM-101 module [Fig. 3(a); GP] converts the ac output of the transducer to a ±5 V dc output; the $+(-)$ sign corresponds to 8.92×10^8 dyne tension (compression). As employed in the stress apparatus, the force transducer will be subject only to a *tensile* force. The module (GP) is specified by the manufacturer to be stable to within 0.25% of the output voltage reading and is powered by a ±15 V, 40 mA power supply (PS). Modules with 0.05% stability are available. A potentiometer (P) can be adjusted for each sample cross section so that the stress can be read directly in any desired units from the digital voltmeter (DVM). This adjustment is possible because the output voltage of the module is directly proportional to the stress. In mks units, the proportionality constant C equals $1.7619/A$ kilobar-mm^2/V, where A is the cross-sectional area of the sample in mm^2. To adjust for direct reading of the stress, the potentiometer (P) is set and locked for a DVM reading of 15 kV with the switch (S) in position A [see Fig. 3(a)]. Then the switch is moved to position B for proper reading of the module output.

A block diagram of the pressure control apparatus is shown in Fig. 3(b). A pressure of 9.4 bars from the nitrogen cylinder (CY) produces a force of 10^9 dynes between the plates of the bellows section. The pressure is applied by placing the three-way valve (TWV) in the vertical position as shown in the figure and is released by turning it to the horizontal position. The toggle valve (TV) and needle valve (NV) allow smooth adjustments of the applied force to within 1 part in 10^4.

A common problem in any uniaxial stress apparatus is the cracking, chipping or breaking of samples under stress. As with previous designs,[8] the maximum stress which can be applied without causing sample damage using the stress cell described here depends on the method by which the sample is epoxied into the cups (Fig. 1B, C). In our case, samples are cut in the form of a rectangular parallelepiped and are polished optically flat on two sets of parallel faces. The ends are ground flat (±0.001 cm) and parallel. The epoxy[12] is placed in the lower cup until it is $\frac{3}{4}$ full. The cup (C) is then heated at 65°C for 20 min until the epoxy becomes

TABLE I. A list of the sources of error in the stress apparatus and associated electronics.

Source of error	Magnitude of error	Error for a 5×10^8 dyne force	Comments on possible reduction of error
1. Linearity of transducer	0.2% of full scale reading	0.4%	See text
2. Stability of module	0.25% of reading	0.25%	Schaevitz makes models that have 0.05% stability
3. Accuracy of digital voltmeter	0.1% of reading +1 digit	0.35%	A $4\frac{1}{2}$ digit DVM would reduce this to 0.1%
4. Accuracy of sample area	0.5%	0.5%	
5. Friction	10^4 dynes	0.025%	Negligible
Total		1.5%	

slightly tacky. This cup is then placed in the cylinder (E) (Fig. 1). The sample is placed in the bottom cup with one end in contact with the epoxy and the other against the bottom of the empty upper cup (B) which is secure in the piston (D). The cups fit tightly around the sample with at most 0.010 cm edge clearance. This tight fit and the contact of the sample against the bottom of the upper cup together produce proper sample alignment. The piston (D) is pressed down by hand to insure that the sample seats firmly in the tacky epoxy. The sample housing is then heated at 90°C for 30 min to cure the epoxy. The process described above is then repeated for the upper cup (B). It is important to note that the cups must not be rotated relative to the cylinder or piston after the expoxy has cured. A rotation of greater than 20° causes a reduction by about a factor of 2 in the maximum stress that can be applied.[13] Samples prepared in this manner and used in the stress apparatus described above have withstood pressures up to 23.0 kilobar along the [110] axis without cracking, chipping, or breaking.

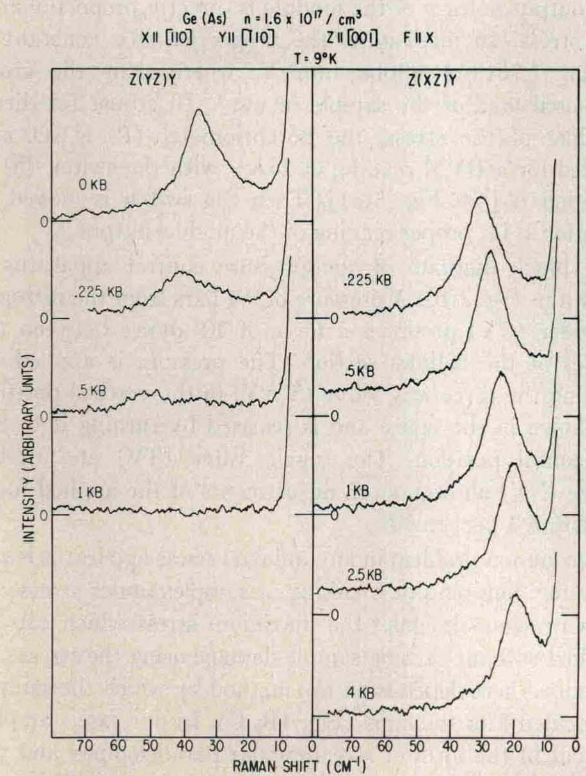

FIG. 4. The Raman spectra of Ge(As) as a function of stress and polarization. Note that the abscissa is linear in wavelength rather than wavenumber. The polarization designations follow standard notation.[24]

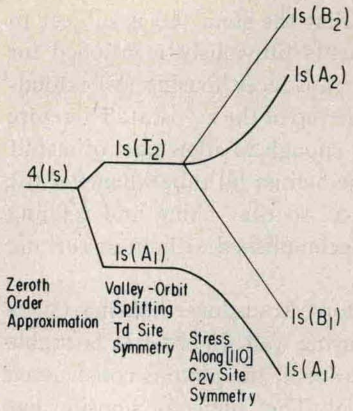

FIG. 5. An energy level diagram of the ground state of an electron bound to an arsenic impurity in germanium and the behavior of these energy levels under the application of uniaxial stress along the [110] axis. The letters in parentheses are the group theoretical designations of the irreducible representations of the point groups T_d and C_{2v}.

The friction between the piston and the cylinder is the only friction in the system which affects the accuracy of our measurements. At room temperature, the static frictional force is less than 10^4 dynes. In order to estimate the over-all accuracy, the measurement error associated with each part of the system must be considered. Table I lists each source of error, its size, its value for a force of 5×10^8 dynes and comments on how the error could be further reduced. The information in Table I suggests that the force transducer is most accurate when the forces it measures are near the maximum force specified for that particular transducer. Our system can easily accommodate force transducers with smaller values of the maximum force. The total estimated accuracy of the present system is $1\frac{1}{2}\%$ for a 5×10^8 dyne force.

To demonstrate that the apparatus described above is a viable research tool, the uniaxial stress dependence of the transmission electronic Raman spectra of Ge(As)[14] is shown in Fig. 4. The spectra of Fig. 4 were excited with an ABC–YAG laser[15] and recorded with a Raman system described elsewhere.[16]

The details of the behavior of the Group V impurities in germanium under uniaxial stress have been extensively discussed elsewhere.[17–19] Briefly, there are four equivalent sites for the electron of a group V impurity in germanium. In the effective mass approximation, the impurity levels are hydrogenic; however, there is an additional perturbation, called the valley-orbit interaction,[17] which is appreciable only for the 1s state and which splits the fourfold degenerate ground state into a singlet and triplet. The singlet and the triplet are designated $1s(A_1)$ and $1s(T_2)$ according to the irreducible representations of the T_d point group. Here T_d is the site symmetry of the arsenic atom. The observation of the $1s(A_1)$ to $1s(T_2)$ valley-orbit Raman transition has been previously reported.[16]

The application of uniaxial stress along the [110] axis of crystalline Ge(As) reduces the site symmetry of the impurity from T_d to C_{2v} and splits the triplet into three singlets[20] as shown in Fig. 5. All possible transitions among the split levels are Raman-allowed; however, at $T=8$K only the A_1 state is significantly populated. While three transitions