

Table V. The agreement between the measured values and the ones calculated by Davis *et al.*<sup>43</sup> would probably improve if Chodorow's potential were used instead of the one derived from the wave functions given by Watson.<sup>49</sup> The strain coefficients of  $E_d$  and  $E_F$  given in Ref. 43 are listed in Table VII.

Using the de Haas-van Alphen effect, Templeton<sup>50</sup> measured the change of the neck area with volume and found  $\partial(\ln A_n)/\partial e = \frac{2}{3}(4.2 \pm 0.2)$ . This information can be used to approximately calculate the strain coefficient of  $E_F$ . It is determined by Eqs. (7) and (18), neglecting the change of the effective mass of the  $L_2'-Q_2-$  band. The numerical value of  $\partial(\ln E_F)/\partial e$  listed in Table VII is about 34% lower than the one derived from the optical experiments. The agreement will be closer if the change of the effective mass is taken into account: Decreasing the volume ( $e > 0$ ) decreases the  $d$ - $sp$  interaction; the  $L_2'-Q_2-$  band will get closer to the free-electron parabola (Fig. 9). Thus, including the change of the effective mass, the same change of the neck area requires a larger value of  $|\partial(\ln E_F)/\partial e|$ .

The  $\Delta R/R$  signal measured with strained polycrystalline films<sup>8,11</sup> shows some resemblance to the functional dependence of the hydrostatic effect ( $Q_{11} + 2Q_{12}$  in Fig. 7), probably with some admixture of the effect produced by trigonal shear strain ( $Q_{44}$ ). Indeed, one would expect the  $\Delta R/R$  signal measured with strained polycrystalline films to be a linear combination of the functions  $Q_{ij}$ , provided the signal is due to the change of the reflectance of the material under study. The function  $Q_{11} - Q_{12}$  is small for Cu and will therefore contribute but slightly to  $\Delta R/R$  measured with polycrystalline films. However, the function  $\Delta R/R$  given in Refs. 8 and 11 is not a simple linear combination of  $Q_{11} + 2Q_{12}$  and  $Q_{44}$ . A positive function which increases with energy has to be added to reproduce  $\Delta R/R$  as presented in Refs. 8 and 11. The maximum value of this function is of the same order of magnitude as the maximum value in  $\Delta R/R$ . We believe that this positive function is identical with an error signal produced, e.g., by the mechanical motion of the film. We also found such an error signal, if present, to be strongly energy-dependent. The functions  $Q_{ij}$  presented here, which are characteristic of electropolished single crystals have zero values below 2 eV. The signal below 2 eV observed using polycrystalline films<sup>8,11</sup> is probably due to the error signal only.

The FS  $\rightarrow L_1$  transition was also identified in the photoemission measurements of Berglund and Spicer.<sup>19</sup>

<sup>49</sup> R. E. Watson, Phys. Rev. 119, 1934 (1960).

<sup>50</sup> I. M. Templeton, Proc. Roy. Soc. (London) A292, 413 (1966).

The energy determined from this experiment is identical with the one reported here. The authors introduced the concept of nondirect transitions in the analysis of their data, i.e., transitions which do not conserve  $k$  directly. The term "indirect transitions" was avoided because the authors wanted to include the possibility that processes different from the usual phonon-assisted transitions are important. The theoretical interpretation of these nondirect transitions is still under discussion (see, e.g., Refs. 51 and 52). Berglund and Spicer concluded from their data that the optical absorption in Cu is dominated by nondirect transitions except for a very small contribution (below 10%) of the direct transitions at  $L$  mentioned above.

It is evident from the results presented here that direct transitions must be important. The structure in  $W_{11} - W_{12}$  which we identified with the  $X_5 \rightarrow X_4'$  transition may serve as an example. One might try to explain it as caused by nondirect transitions starting from various initial states to the same final state  $X_4'$ . The  $k$  degeneracy of  $X_4'$  will be lifted by tetragonal shear strain. This might cause the observed  $W_{11} - W_{12}$ . However, the selection rules for nondirect transitions will generally differ from those for direct transitions. The assumption  $|M_x|^2 = |M_y|^2 = |M_z|^2$  might be adequate for such an averaging process. In this case, there would be no first-order change of  $\epsilon_2$  at all, i.e.,  $W_{11} - W_{12}$  would be zero, in contrast to the experimental result reported here.

The sign ( $X$  transition) as well as the magnitude ( $L$  transition) of the observed energy shift is consistent with the selection rules for direct transitions. Thus the nondirect transitions must have selection rules identical to those for direct transitions in order to be compatible with our measurements.

The photoemission measurements<sup>19</sup> on Cu can also be explained if one assumes that the absorption above 2 eV is dominated by direct interband transitions.<sup>51</sup> It is more natural to discuss the optical absorption in this region in terms of direct transitions, because this process is well established theoretically and accounts for all details of the experiments presented in this paper.

#### ACKNOWLEDGMENTS

I should like to thank Professor H. Fritzsche for numerous valuable suggestions and discussions during the course of this research. I am also grateful to Professor D. Beaglehole, Dr. T. Halpern, Dr. F. M. Mueller, and Dr. R. Sandrock for their help and advice.

<sup>51</sup> W. E. Spicer, Phys. Rev. 154, 385 (1967).

<sup>52</sup> R. K. Nesbet and P. M. Grant, Phys. Rev. Letters 19, 212 (1967).

<sup>53</sup> U. Gerhardt (to be published).