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# Galvanic Contact Deposition of CdTe Layers Using Ammoniacal Basic Aqueous Solution

**Kentaro Arai, Souichi Hagiwara, Kuniaki Murase,* Tetsuji Hirato,* and Yasuhiro Awakura**[z]

*Department of Materials Science and Engineering, Kyoto University, Kyoto 606-8501, Japan*

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The galvanic contact deposition of CdTe layers from ammoniacal basic solutions was carried out, and their deposition behaviors were investigated. The structural and electrical properties of deposits were examined and then compared with those of deposits prepared by normal electrodeposition from the same solutions. The cathode potential was always spontaneously kept at around −0.7 V *vs.* standard hydrogen electrode during the contact deposition although CdTe also deposited on the Cd sheet, that is, the anode. The current density gradually decreased with time just like that in the normal potentiostatic electrodeposition. The current efficiency was approximately 100% under illumination, whereas it was less than 50% in the dark. These behaviors were the same as those observed in normal electrodeposition from the same electrolytes. The resulting deposits both under illumination and in the dark were polycrystalline CdTe layers with almost stoichiometric composition. The as-deposited CdTe layer had a p-type conduction with resistivity of the order of $10^7\ \Omega$ cm.

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Cathodic electrodeposition is one of the key techniques for the preparation of thin-layered compound semiconductors (*e.g.*, CdTe and $CuInSe_2$) for solar cell applications, and the cell made up of an n-CdS/p-CdTe heterojunction has been put into production on an industrial scale. Since the pioneering work of Kröger's group in the late 1970s, aqueous acidic sulfate solutions have historically and almost exclusively been employed as the bath for CdTe electrodeposition. In contrast, we have proposed that aqueous basic, or alkaline, solutions containing ammonia or amine ligands are also suitable for the electrodeposition of a uniform CdTe layer, because these basic solutions have a relatively high solubility of Te(IV) species as $TeO_3^{2-}$ ions.

The deposition of stoichiometric CdTe takes place at potentials positive to the Nernst potential for elemental Cd deposition. Regarding the acidic baths, Kampmann *et al.* found that a deposition potential of only +5 mV *vs.* the elemental Cd deposition led to the formation of CdTe with relatively high crystallinity.[1] Although the basic solution gave CdTe layers having a lower crystallinity compared to the layers from the acidic baths, the nearer the deposition potential approaches the potential for elemental Cd, the higher the CdTe deposition current becomes. Hence, a positive control of cathode potential during the electrodeposition of CdTe layer is of importance for both acidic and basic baths. On a laboratory scale, electrodepositions under controlled potentials, *i.e.*, potentiostatic electrodepositions, are easily conducted by a three-electrode setup using a potentiostat and nonpolarizable reference electrode together with a Luggin capillary. However, when upscaled to an industrial level, most electrodeposition processes are reorganized to be current controlled, *i.e.*, galvanostatic electrodepositions, to avoid the complexity arising from the three-electrode configurations, while such galvanostatic conditions may result in a large fluctuation in deposition potential.

Without the potentiostat and reference electrode, the potential of the working electrode, *i.e.*, the deposition substrate, for cathodic electrodeposition can be held almost constant using the galvanic contact plating technique. In this technique, the substrate is short-circuited to an auxiliary electrode, of which the potential when immersed into the electrodeposition bath, or into another solution connected electrically with the electrodeposition bath, is negative to the Nernst potential for the deposition of the desired substance. In other words, the substrate and the auxiliary electrode constitute a short-circuited galvanic cell, where the former acts as cathode and the latter as anode. Such a galvanic contact plating may make possible CdTe deposition under "semipotentiostatic" conditions.

Figure 1 shows a set of potential-pH diagrams of the $Cd\text{-}NH_3\text{-}H_2O$ and $Cd\text{-}Te\text{-}NH_3\text{-}H_2O$ systems for the basic region.[2,3] As mentioned, the deposition of stoichiometric CdTe takes place at potentials positive to the Nernst potential ($E_{Cd}$) for bulk Cd deposition

$$Cd(NH_3)_4^{2+} + 2e \rightleftharpoons Cd + 4NH_3 \qquad [1]$$

According to the diagram of the $Cd\text{-}NH_3\text{-}H_2O$ system, the potential $E_{Cd}$ at pH 10-11, where CdTe electrodeposition from ammoniacal basic baths is usually conducted by the authors' group, is about −0.73 V *vs.* standard hydrogen electrode (SHE). In the same pH range, the positive limit for the CdTe electrodeposition is sectioned by the reaction

$$Cd(NH_3)_4^{2+} + Te + 2e \rightleftharpoons CdTe + 4NH_3 \qquad [2]$$

of which the Nernst potential ($E_{CdTe}$) is around −0.22 V. These imply that the galvanic contact plating of CdTe deposition can be realized using a Cd metal electrode as the auxiliary electrode, *i.e.*, anode. Under this concept, the galvanic contact plating of CdTe from conventional acidic media using the Cd auxiliary electrode was examined by Bhattacharya *et al.* in the early 1980s. However, in this case, the use of Cd electrode as the anode seems to be a drawback to the process, because the use of a soluble Te anode for continuous feeding of Te(IV) ions is practical, owing to the low solubility of Te(IV) ions to the baths. In the field of semiconductor electrodeposition, CdS,[4] CdSe,[5] ZnTe,[6] and CdTe[7] layers have also been prepared by the galvanic contact plating using acidic media.

In the present study, we tried using basic ammoniacal baths for the galvanic contact deposition of CdTe. Here, a photo-assisted growth technique of CdTe[2] was employed. The deposition phenomena and the properties of the resulting CdTe layer, *i.e.*, stoichiometry, morphology, and electrical properties, were compared with those electrodeposited using an external current source.

## Experimental

*Deposition of CdTe*.—Basic aqueous electrolytes were prepared by dissolving 40-60 mM $CdSO_4 \cdot 8/3H_2O$ and 10 mM $TeO_2$ in an ammoniacal buffer solution containing 4.0 M $NH_3$(aq) and 0.5 M $(NH_4)_2SO_4$.[8] All chemicals (Nacalai Tesque, Inc.) were of reagent grade and were used without pretreatment. The deionized (DI) water used to prepare the ammoniacal buffer had a specific resistance larger than $5 \times 10^6\ \Omega$ cm. The pH of the pre-prepared ammoniacal buffer, where $[NH_3] + [NH_4^+] = 5.0$ M, was 10.7 at 25°C and did not change by addition of $CdSO_4 \cdot 8/3H_2O$ and $TeO_2$; Cd(II) and Te(IV) species in the electrolytes were thus dissolved to form $Cd(NH_3)_4^{2+}$ and $TeO_3^{2-}$ ions, respectively. An Ag/AgCl electrode (Horiba 2080A-06T) immersed in 3.33 M KCl was used as a refer-

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* Electrochemical Society Active Member.

[z] E-mail: yasuhiro.awakura@materials.mbox.media.kyoto-u.ac.jp

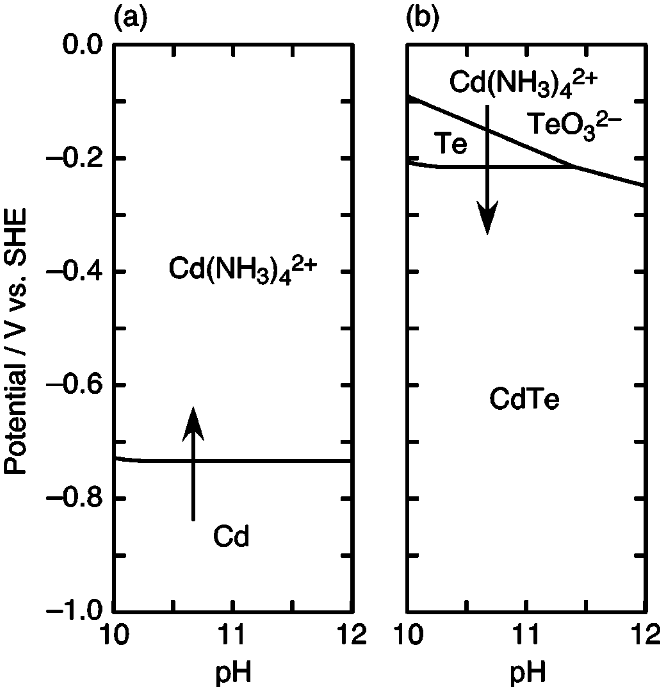

**Figure 1.** Potential-pH diagrams of (a) Cd-$NH_3$-$H_2O$ and (b) Cd-Te-$NH_3$-$H_2O$ systems for basic region at 298 K calculated assuming activities of dissolved Cd(II) and Te(IV) species and total ammonia concentration are 0.06, 0.01, and 5.0 M, respectively. Two arrows correspond to the process expected for (a) anode and (b) cathode reactions during galvanic contact deposition.

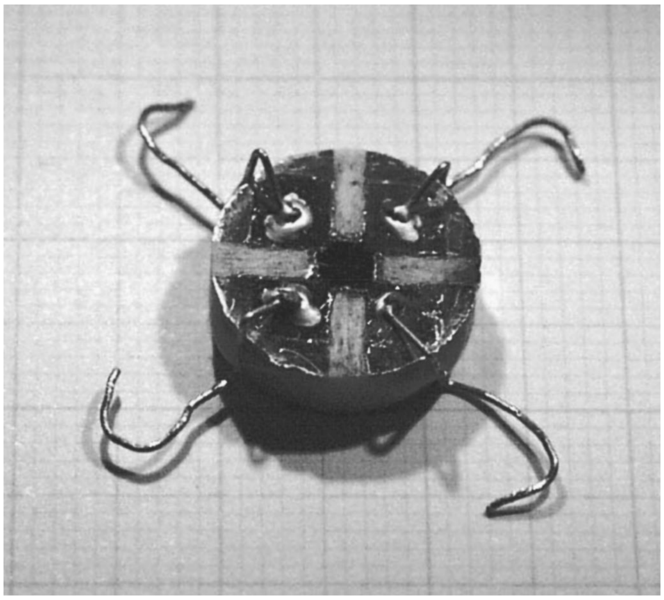

**Figure 2.** Typical picture of a sample for measurements of electrical properties. The sample has four small Au contacts in four vertices of square CdTe on nonconductive epoxy resin.

ence to measure the cathode potential; the potentials were recalculated for the SHE. A Cd sheet (99.99%; Nilaco Corp.) 100 × 15 mm in area and 1.5 mm thick was used as the anode. The Cd sheet was pretreated with 3 M HCl solution for 3 min and then rinsed with DI water before each experimental run. The electrochemically active area of the Cd sheet immersed in the electrolyte for CdTe deposition was 6 $cm^2$ in total. A gold-plated copper sheet polished with 0.3 μm alumina abrasive was used for the cathode substrate; the thickness of the Au plating was 1-3 μm. A part of the Au/Cu sheet surface was covered with Teflon adhesive tape so that a set of two squared areas (about 10 × 10 mm) was exposed to the electrolytes as the surface of the substrate. The deposit on one square was transferred onto an epoxy resin to examine the electrical properties, and that on the other was used for characterization of the crystallinity, composition, and thickness. The current was measured by using a zero-shunt ammeter (Hokuto Denko HM-101) connected to a coulometer (Hokuto Denko HF-201), and the cathode potential was monitored with a conventional digital voltmeter. The solution was thermostatted at 343 K (70°C) and stirred at approximately 500 rpm. CdTe deposition was performed under white light irradiation or in the dark. A 500 W xenon arc lamp (Wacom KXL-500F) installed in a lamp housing was used for the irradiation. The approximate integrated irradiance of the white light just before the electrolytic vessel was 300 mW $cm^{-2}$. When deposited in the dark, the electrolytic cell was placed in a light-resistant box to eliminate any photo effects on the growing CdTe. The concentration of Cd(II) ions was set at 40 mM under illumination and 60 mM in the dark, as optimized for electrodeposition from ammoniacal basic electrolytes.[2]

*Analysis of deposits*.—The morphology and crystallinity of the resulting deposits were examined with an X-ray diffractometer (Rigaku RINT 2200) fitted with a molybdenum X-ray tube. All the X-ray diffraction (XRD) measurements were scanned in 2θ-θ mode. The thickness of the deposits was measured by surface texture measurements (Tokyo Seimitsu 1400D-12M). The compositions of the deposits were determined by electron probe microanalysis (EPMA). A single crystal of CdTe having a composition of 50.00 atom % Cd was used as the standard for EPMA. The reflectivity spectra of deposits were measured by a spectrophotometer (Hitachi U-3500) with an integrating sphere to determine the bandgap energy.

*Hall effect measurement*.—The CdTe layer was transferred from the Au/Cu substrate onto nonconductive epoxy resin (Torr Seal; Varian Associates) for electrical characterization.[8] After transferring the CdTe layer, four Au electrodes (70-100 nm thick) were deposited by vacuum evaporation through a cross-shaped mask using two strips of aluminum foil; the width of the strips, that is, the distance between each pair of adjacent Au electrodes, was 2 mm. Then, four parts of the CdTe layer exposed in between each adjacent pair of Au electrodes were scraped off with a cutter knife. In this way, a sample for electrical characterization, having four ideal small Au contacts in four vertices of square CdTe, could be obtained. Four Au wires were fixed onto the side of the underlying epoxy resin with quick-drying glue, and one end of each of the four Au wires was attached to each of four Au electrodes with silver paste. Figure 2 shows a typical picture of the sample.

The resistivity and Hall effect were measured at room temperature with a resistivity/Hall measurement system (Toyo Corp. ResiTest 8310) using the van der Pauw method. The resistivity of the CdTe layer was so high (*e.g.*, $10^8$ Ω cm) that Hall voltage measurement by the conventional dc mode was impossible for our CdTe deposits. Therefore, the ac magnetic field method was employed for the measurement. The magnitude and frequency of the magnetic field were 0.6 T at the maximum and 50 mHz, respectively. The conduction type was distinguished by a phase shift between the magnetic field and the Hall voltage; for this system, the type was determined to be p- or n-type when the shift was in the range −60 to 30° or 120-210°, respectively. The density and mobility of the majority carrier were calculated from the absolute value of the Hall voltage.

## Results and Discussion

*Deposition behavior of CdTe*.—The open-circuit potentials of the Au/Cu substrate and Cd sheet before CdTe deposition were around 0.0 and −0.71 V, respectively. The two electrode potentials became almost equal when the Au/Cu substrate was short-circuited

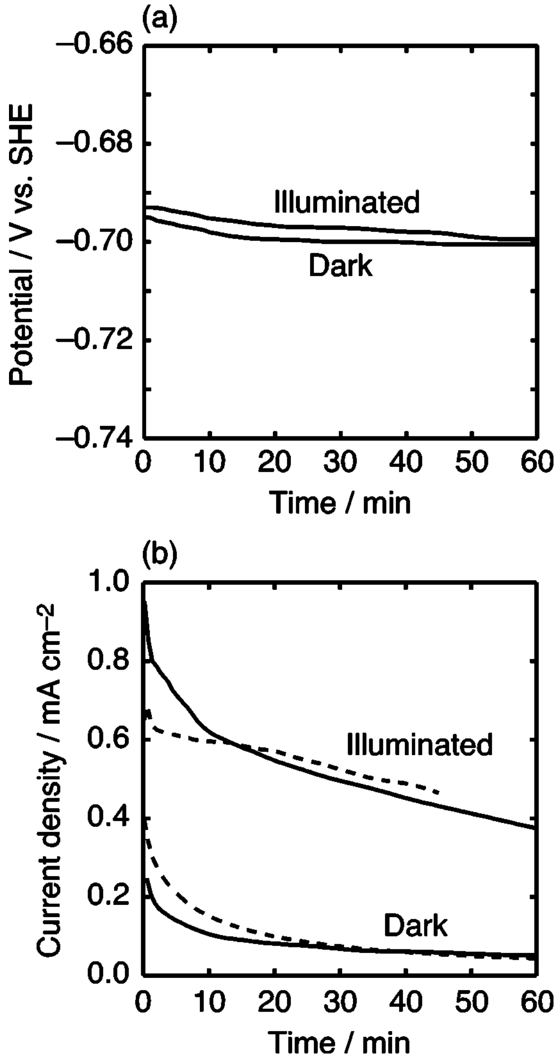

**Figure 3.** Variation of (a) cathode potentials and (b) current densities during galvanic contact deposition. Dashed lines in (b) are current during normal electrodeposition under illumination and in the dark.

to the Cd sheet. Figure 3 illustrates the variation of cathode potentials and current densities during the deposition under illumination or in the dark. The cathode potentials were spontaneously kept at around −0.7 V throughout the deposition both under illumination and in the dark, indicating that a potentiostatic situation was more or less realized without an external potentiostat with a reference electrode. Note that the potential −0.7 V is almost the same as that of the potential optimized for CdTe normal electrodeposition from ammoniacal basic electrolytes using a conventional potentiostat. Figure 4 illustrates a set of schematic polarization curves for redox reactions

$$Cd(NH_3)_4^{2+} + TeO_3^{2-} + 4e + 6H^+ \rightleftharpoons CdTe + 4NH_3 + 3H_2O \tag{3}$$

and Reaction 1. The curves are given as a relationship between the electrode potentials and the logarithm of the current. During galvanic contact deposition, the electrode potentials of the Au/Cu substrate ($E_c$) and the Cd sheet ($E_a$) become almost equal, when the IR-drop in the solution and lead wire is negligible. In this case, the forward process of the electrochemically nobler reaction (Reaction 3), *i.e.*, cathodic deposition of CdTe, takes place on the Au/Cu substrate, while the backward process of the less noble reaction (Reaction 1), *i.e.*, anodic dissolution of Cd, occurs on the Cd sheet. Here, the exchange current density of Reaction 1, the redox of Cd, *i.e.*, a normal metal, is expected to be higher than that of CdTe deposition (Reaction 3) involving the redox of irreversible oxyanion $TeO_3^{2-}$. Furthermore, the CdTe deposition is suppressed by the adsorption of Cd(II)-ions, resulting in a smaller Tafel slope of the polarization curve for Reaction 3.[9] As a result of the difference in polarization curves for the reactions, the potential $E_c(=E_a)$ during the contact deposition is expected to be close to the Nernst potential of Reaction 1. If a Cd anode with a smaller surface area is employed, the deposition proceeds at a more positive potential.

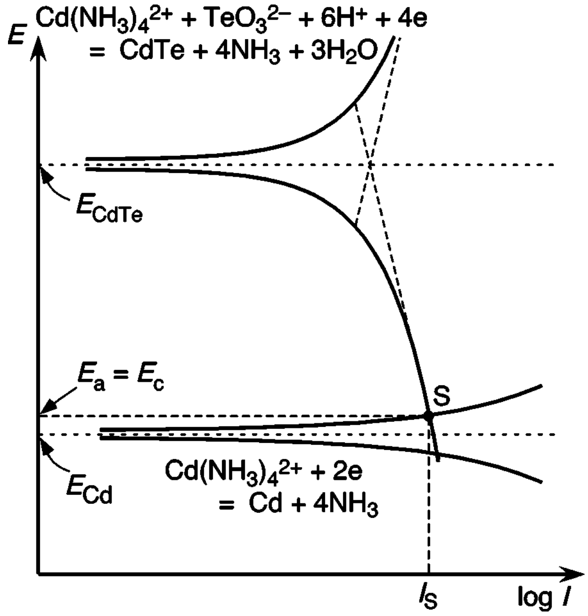

**Figure 4.** Electrode potentials of Au/Cu substrate and Cd sheet *vs.* logarithm of current in galvanic contact deposition. It is assumed that Reactions 3 and 1 occur on Au/Cu substrate and Cd sheet, respectively.

The initial current density under illumination was about 1.0 mA $cm^{-2}$, while that in the dark was lower, 0.30 mA $cm^{-2}$. In both cases, the currents gradually decreased as the time elapsed. These behaviors were observed in the case of normal electrodeposition of CdTe from the same electrolytes.[2] In the previous work,[2] we conclude that the photo effect on the growth of CdTe is caused by a photoconduction, where an extremely low carrier density, *i.e.*, electron density, of the resulting CdTe layer in the dark is increased by the irradiation of visible light, which is pumping up electrons to the conduction band. By this photo-assisted deposition, it took 60 min to flow the charge of 1.5 C $cm^{-2}$, *vs.* 1694 min in the dark condition.

After the CdTe deposition, it was revealed by XRD and EPMA that CdTe was also deposited on the Cd sheet that is an anode. The formation of CdTe on the Cd sheet is explained by a simple displacement reaction

$$3Cd + TeO_3^{2-} + 8NH_3 + 6H^+ \rightarrow 2Cd(NH_3)_4^{2+} + CdTe + 3H_2O \tag{4}$$

which proceeds spontaneously due to the negative Gibbs free energy change ($\Delta G$) of the reaction: −529 kJ $mol^{-1}$ at 298 K, pH 10.7, $a_{TeO_3^{2-}} = 0.01$, and $a_{Cd(NH_3)_4^{2+}} = 0.06$; here a set of thermochemical data in Table I of Ref. 3 was used for the calculation. Once the Cd sheet is thoroughly covered with the CdTe layer, the CdTe growth on the Au/Cu substrate is expected to cease, as the potential control by $Cd/Cd^{2+}$ redox is lost. However, the deposition of CdTe on the Au/Cu substrate took place continuously even after the deposition of CdTe on the Cd sheet. It seems that the continuous potential control and the deposition of CdTe on the Au/Cu substrate was achieved by the presence of cracks in CdTe on the anode. Through the cracks, Cd

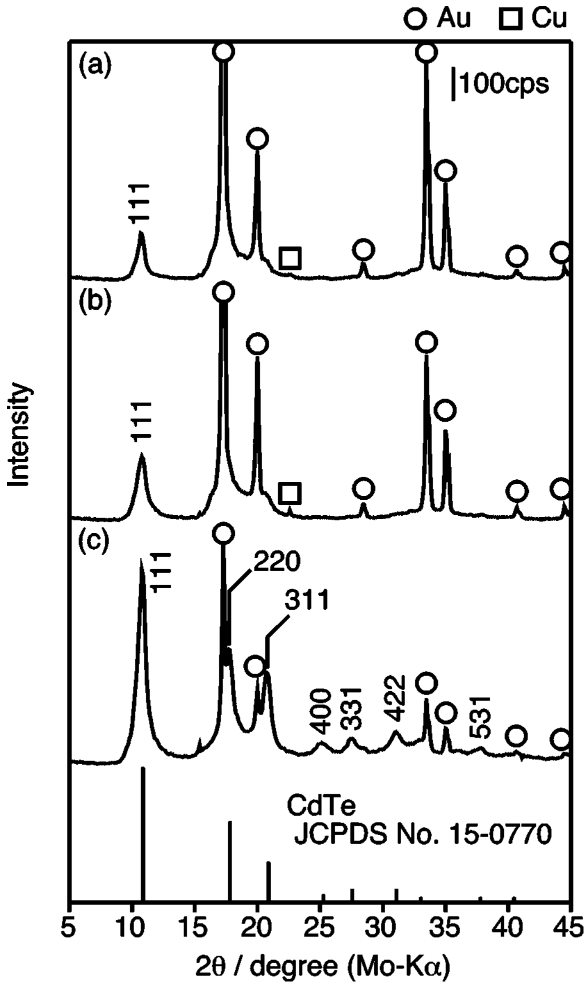

**Figure 5.** XRD patterns of deposits by galvanic contact deposition (a) in the dark and (b, c) under illumination. Thickness of deposits: (a) 0.6 μm, (b) 1.3 μm, (c) 13.5 μm.

can make contact with the solution, and the electrode potential was kept negative. Such a displacement reaction on the Cd sheet can be avoided by using a two-conpartment cell where an electrolyte without Te(IV) ions is used as an anolyte.

*Morphology of deposits*.—Figure 5 shows typical XRD patterns of deposits made under illumination or in the dark. Every diffraction peak could be assigned to that of CdTe and Au/Cu substrate; no peaks attributable to elemental Cd or Te were observed. This indicates that both deposits under illumination and in the dark consist of a single phase of polycrystalline CdTe. CdTe layers electrodeposited from ammoniacal basic electrolytes have random orientations and mean crystallite sizes of approximately 10 nm.[10] CdTe deposits by contact deposition appeared to have a ⟨111⟩ preferential orientation for the thinner deposits (a and b), because the reflections other than 111 index (2θ = 10.9°)[11] were not clearly seen due to their weak intensity. We have found that CdTe layers prepared from the ammoniacal electrolyte using normal potentiostatic electrodeposition have a random orientation irrespective of their thickness.[10] However, each of the first and second peaks of the substrate has a weak shoulder corresponding to 220 and 331 reflections. The XRD pattern of the thicker deposit (c) gave other reflections such as 220 (2θ = 17.8°), 331 (20.9°), 400 (25.3°), 331 (27.6°), and 422 (31.1°) due to the stronger intensity.[11] The relative intensities of the reflections were similar to those of powder data, suggesting that the contact deposited CdTe layers also have a random orientation. The mean crystallite sizes of the CdTe deposits estimated from the half-width of the 111 diffraction peak using Scherrer's equation were about 10 nm, independent of thickness.

*Composition and current efficiency*.—The composition, thickness, and current efficiency of the resulting deposits are summarized in Table I. The current efficiency was calculated from the total charge passed, the density of CdTe (5.9 g cm$^{-3}$), and the thickness of the deposits. Both under illumination and in the dark, the compositions of the deposits were nearly stoichiometric (49.4-49.6 atom % Cd), although they were slightly richer in Te, as is often the case with normal electrodeposition. Figure 6 depicts typical surface and cross-sectional scanning electron microscopy (SEM) images of a CdTe layer deposited under illumination. The sample for the cross-sectional SEM observation was prepared by cutting the substrate with the CdTe layer using a diamond wheel saw followed by mechanical polishing of the resulting cross section with a set of emery papers and then with alumina abrasives (1.0 and 0.3 μm); a handmade stainless holder was employed for the mechanical polishing. When assessed from the SEM image, it was found that the CdTe layer was closely and uniformly grown on the substrate. By EPMA line analysis along the white line in Fig. 6, it was confirmed that the ratio of Cd and Te was almost constant in the direction of film thickness. The thickness of the CdTe layer determined from the image was about 13.5 μm, which is in agreement with that measured by the surface texture measurements.

The current efficiency of the deposition was less than 50% in dark conditions, and there was a tendency for the efficiency to decrease with increasing thickness of the deposits. However, under illumination, the current efficiency of the deposition was approximately 100% independent of the thickness. This tendency of current efficiency was also observed in normal electrodeposition from the basic electrolytes.[2] One of the plausible side reactions which lowers the current efficiency is the reduction of dissolved oxygen and/or hexavalent Te(VI) ions as

$$O_2 + 4H^+ + 4e \rightarrow 2H_2O \qquad [5]$$

$$TeO_4^{2-} + 2H^+ + 2e \rightarrow TeO_3^{2-} + H_2O \qquad [6]$$

Although tellurium ions are initially dissolved as tetravalent Te(IV) ions, they can be spontaneously oxidized by dissolved oxygen as

$$2TeO_3^{2-} + O_2 \rightarrow 2TeO_4^{2-} \qquad [7]$$

because $E^\circ_{Te(IV)/Te(VI)}$ at pH 10.7 is 0.26 V,[12] which is lower than the $E^\circ_{H_2O/O_2}$ of 0.60 V. It is assumed that the difference of current efficiency under illumination and in the dark is attributable to the difference of each deposition rate. Given that half of the current is caused by the side reaction in dark conditions and that the side

**Table I. Total charge passed and time during deposition, thickness and composition of deposits, and current efficiency. Current efficiencies calculated from total charge and volume of deposits.**

| | Total charge (C cm$^{-2}$) | Depositiontime(min) | Thickness (μm) | Composition (atom % Cd) | Currentefficiency(%) |
|---|---|---|---|---|---|
| Under illumination | 1.9 | 60 | 1.3 | 49.6 | 97 |
| | 18.8 | 1980 | 13.5 | 49.5 | 100 |
| In the dark | 1.9 | 1694 | 0.6 | 49.4 | 46 |
| | 8.3 | 8220 | 1.7 | 49.6 | 29 |

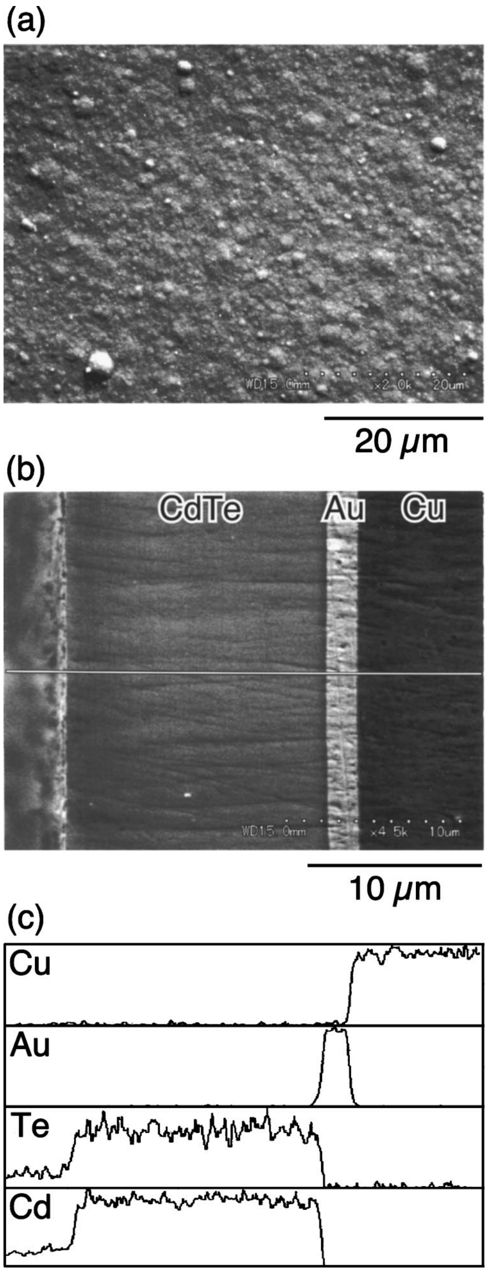

**Figure 6.** Typical (a) surface and (b) cross-sectional SEM images of CdTe deposited by galvanic contact deposition, and (c) line analysis along the white line in (b) by EPMA. Thickness of deposits was determined to be 13.5 μm.

reactions are limited by mass transfer from the solution bulk to the cathode, only the current for CdTe deposition can increase due to illumination. In this case, the current efficiency under illumination is calculated to be approximately 90%. If that is the case, it is expected in dark conditions that the Te(VI) species accumulate in the solution with time elapsed, and, hence, the current efficiency decreases. As a result, the current efficiency for the deposition for 8820 min was lower than that for 1694 min (see Table I). Recently, we have examined *in situ* the change in the current efficiency during normal electrodeposition using an electrochemical quartz crystal microbalance. Here, the current efficiency was increased up to 90-95% in the earlier stage of the electrodeposition, and afterwards it gradually decreased to 60-80%.[13]

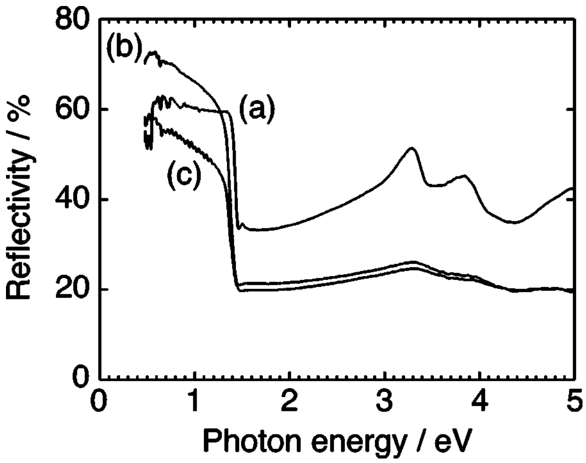

**Figure 7.** Reflectivity spectra of (a) single-crystal CdTe plate and CdTe layers prepared by (b) galvanic contact deposition and (c) electrodeposition from ammoniacal basic electrolyte. Single-crystal CdTe plate was 1 mm thick. Both contact deposited and electrodeposited CdTe were 5 μm thick.

*Evaluation of the bandgap energy*.—Figure 7 shows the reflectivity spectra of CdTe prepared by galvanic contact deposition and by normal electrodeposition compared with that of the single-crystal CdTe. The thickness of the CdTe layers prepared by contact deposition and by normal electrodeposition was approximately 5 μm. The single-crystal CdTe was a plate 1 mm thick. In all the spectra, a decrease in the reflectivity was observed at almost the same energy, which was attributed to the bandgap energy. The bandgap energy of the contact deposited CdTe evaluated from the spectra was 1.45 eV, the same as that of both the electrodeposited and single-crystal CdTe. However, the reflectivity gradually decreased from the energy below 1 eV in the contact deposited and normal electrodeposited CdTe, whereas the decrease in the reflectivity was very steep in the single-crystal CdTe. In other words, the absorptions at the bandgap energy of both the contact deposited and normal electrodeposited CdTe were less clear than that of the single-crystal CdTe. This indicates that both the contact deposited and normal electrodeposited CdTe have some located impurity energy levels which were attributed to several defects such as Cd or Te vacancies and grain boundaries.

*Electrical properties*.—The usual thickness of CdTe layers employed for a CdTe/CdS solar cell is 1-2 μm. Therefore, the electrical properties of CdTe in such a thickness range may be of interest in view of practical applications. However, the electrical properties of thin CdTe layers (below 3 μm thick) could not be determined due to the high resistivity of CdTe. Therefore, the electrical properties were measured for thicker layers (more than 10 μm). In this case, the layers were prepared under illumination; it was difficult to prepare such thick layers in the dark due to a slow deposition rate. The resistivity of the as-deposited CdTe layer (13.5 μm thick) determined by the van der Pauw method was $5.5 \times 10^7$ Ω cm, which is the same level as that of CdTe electrodeposited from acidic electrolytes ($10^4$–$10^8$ Ω cm)[14-16] and from basic electrolytes ($10^7$ $-10^9$ Ω cm).[8] The conduction type of the CdTe was p-type in analogy with CdTe layers electrodeposited from the same basic electrolytes, whereas CdTe layers electrodeposited from acidic electrolytes are usually n-type when the deposition potential is close to the Nernst potential for bulk Cd deposition.

The carrier density of CdTe deposited by galvanic contact deposition was $4.4 \times 10^{11}$ $\text{cm}^{-3}$, which was five orders of magnitude larger than that of intrinsic CdTe (*ca.* $10^6$ $\text{cm}^{-3}$).[8] The Fermi level $E_F$ for the CdTe layer was calculated from the value of the carrier density, which was equal to the hole density in this case, by the following equation to be located at 0.42 eV above the top of the valence band

$$p = N_V \exp\{-(E_F - E_V)/kT\} \qquad [8]$$

$$N_V = 2(2\pi m_h^* kT/h^2)^{3/2} \qquad [9]$$

where $p$ is the hole density, $N_V$ is the effective density of states in the valence band, $E_V$ is the energy of the top of the valence band, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $m_h^*$ is the effective mass of the hole; $m_h^* = 0.35m$ ($m$: mass of free electron),[16] and $h$ is the Planck constant. The value of the Fermi level 0.42 eV of this CdTe film is the same level as that of the electrodeposited CdTe films with p-type conduction.[8,17,18]

The hole mobility for the CdTe layer was 0.24 cm$^2$ V$^{-1}$ s$^{-1}$, which lay in the same level as that for electrodeposited CdTe and was much smaller than those reported for single-crystal CdTe (50-100 cm$^2$ V$^{-1}$ s$^{-1}$).[19-22] Considering that the grain size of the CdTe is as small as 10 nm, the origin of the small mobility of the CdTe may be the trapping of carriers at grain boundaries.[23,24]

## Conclusion

Flat, smooth, polycrystalline CdTe layers were deposited from ammoniacal basic aqueous solution by a galvanic contact deposition technique. All the features and the deposition behavior of the CdTe layer were the same as those observed for normally electrodeposited CdTe using an external current source. The current density could be increased by irradiating white light to the cathode surface during deposition. All the CdTe deposits were nearly stoichiometric (49.4-49.6 atom % Cd). In dark conditions, the current efficiency of deposition was less than 50% and the thicker the deposits, the more the efficiency decreased. However, under illumination, the current efficiency of deposition was approximately 100% independent of thickness. The bandgap energy of the contact deposited CdTe was evaluated as 1.45 eV, which was almost the same as that of the single-crystal CdTe. The conduction type of the CdTe deposited by galvanic contact deposition was p-type, and the resistivity, carrier density, and mobility were $5.5 \times 10^7$ Ω cm, $4.4 \times 10^{11}$ cm$^{-3}$, and 0.24 cm$^2$ V$^{-1}$ s$^{-1}$, respectively.

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